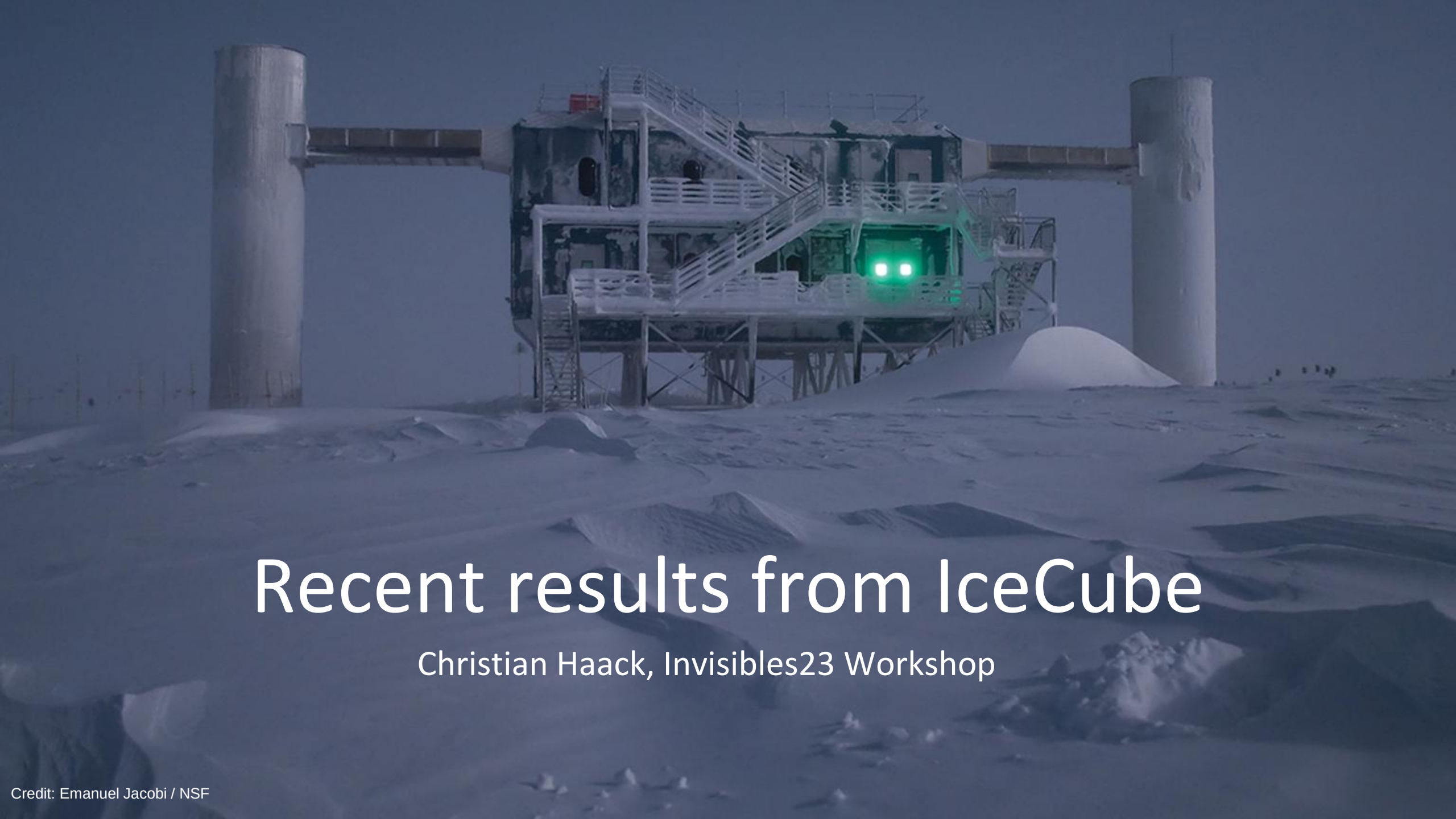


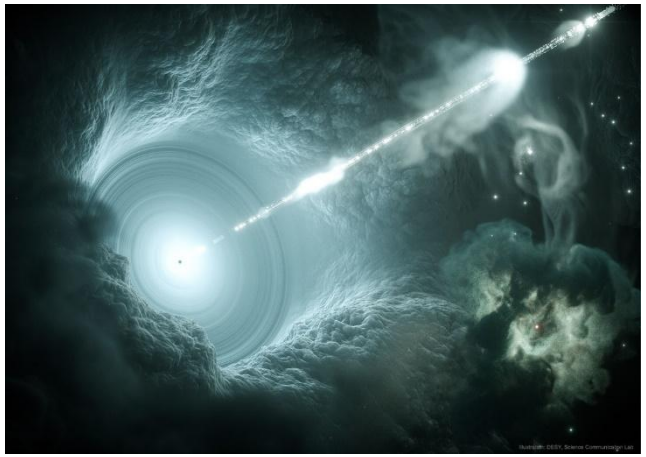
Recent results from IceCube

Christian Haack, Invisibles23 Workshop

Credit: Emanuel Jacobi / NSF

Detection Method

Astrophysical Accelerator



DESY

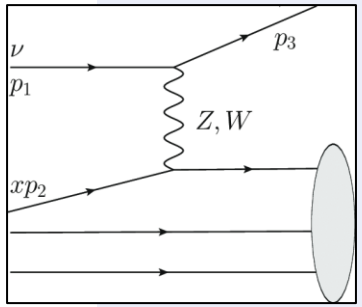
Neutrinos

Transparent Natural Medium (Water / Ice)

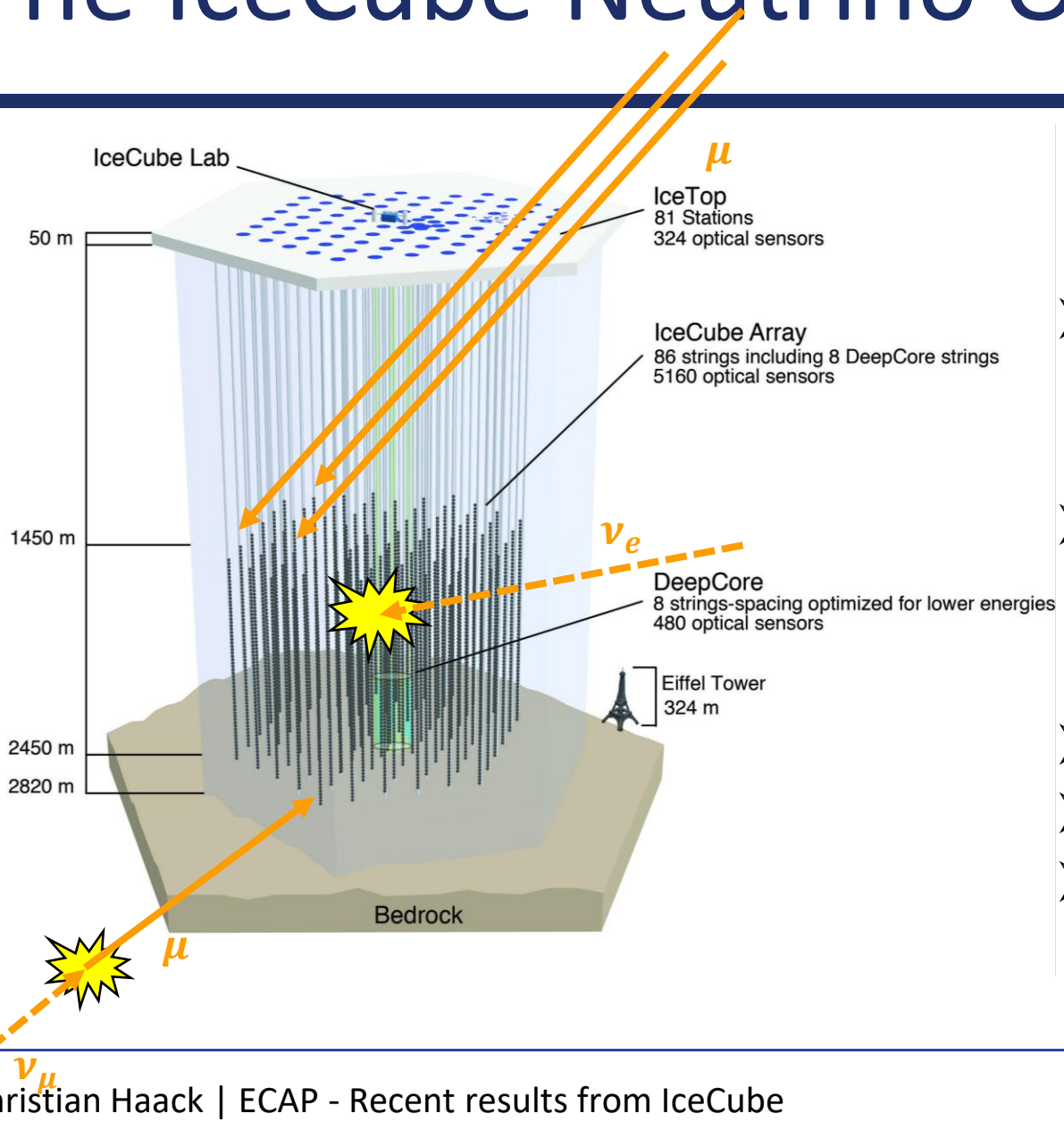
Secondaries

Photons (Cherenkov)

Strings with photosensors

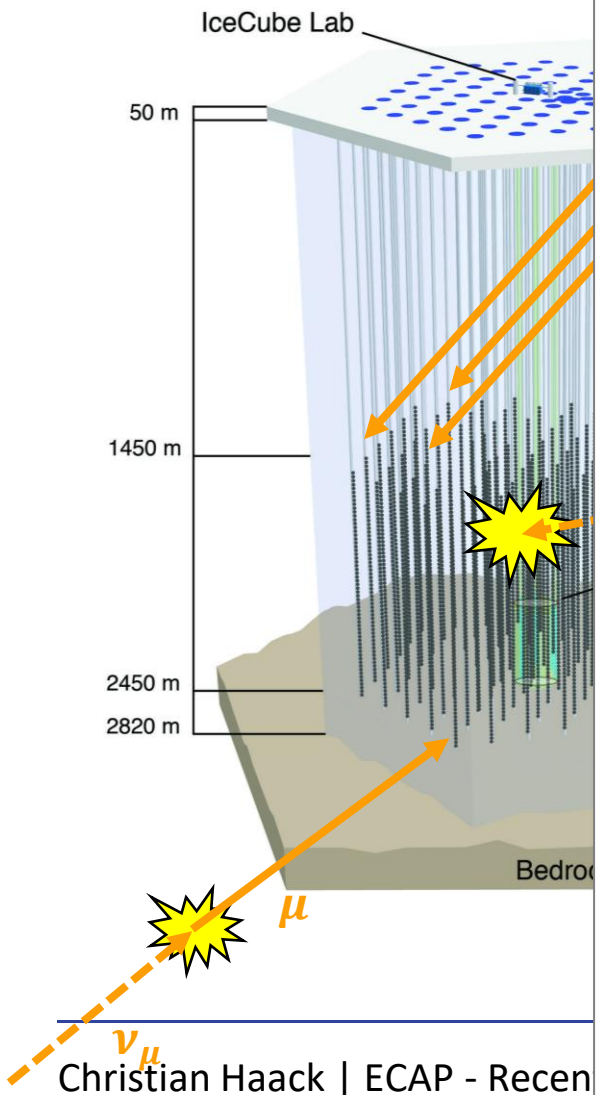


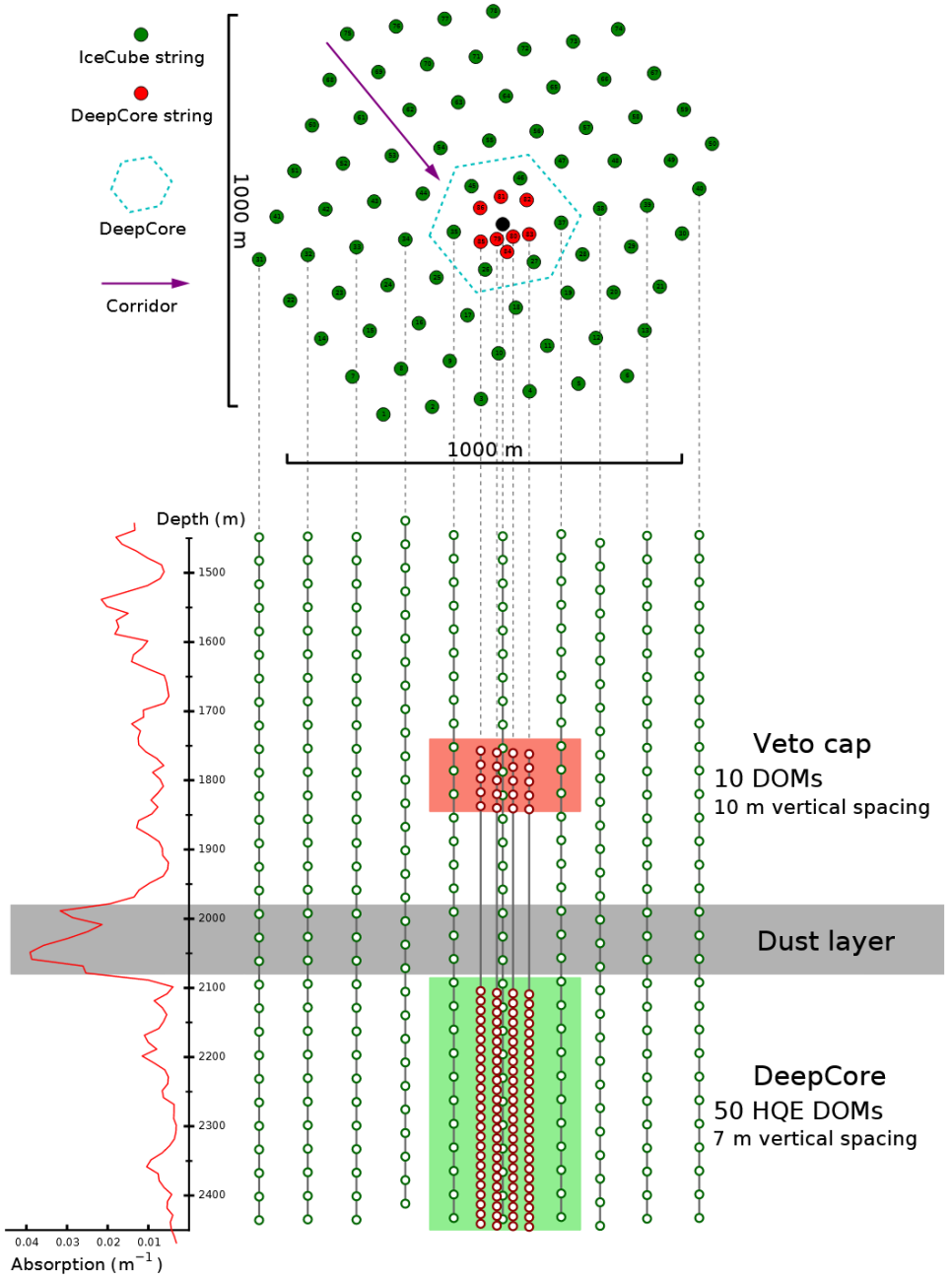
The IceCube Neutrino Observatory



- 86 Strings with 60 Digital Optical Modules (DOMs)
- Full configuration running with > 99% uptime since 2011
- 3000 atmospheric μ per second
- 1 atmospheric ν per minute
- 1 astrophysical ν per day

The IceCub ory



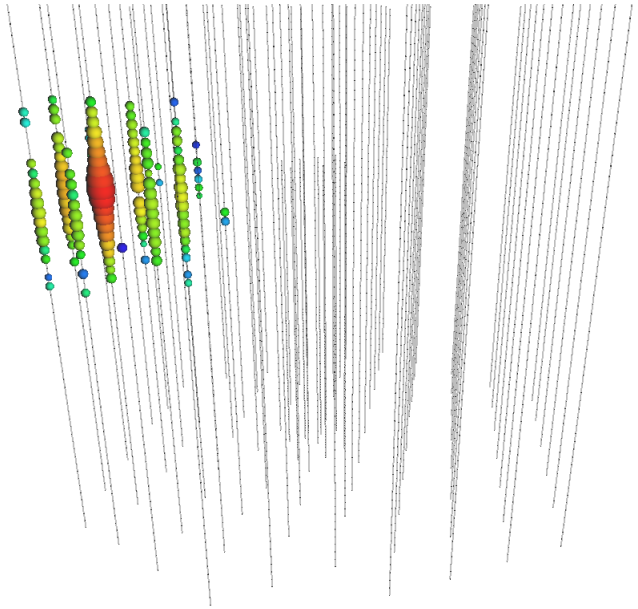


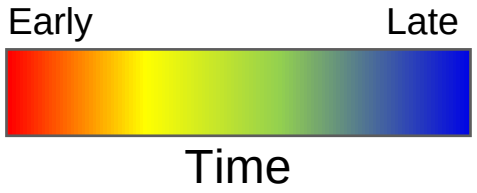
n 60 Digital Optical
Ms)

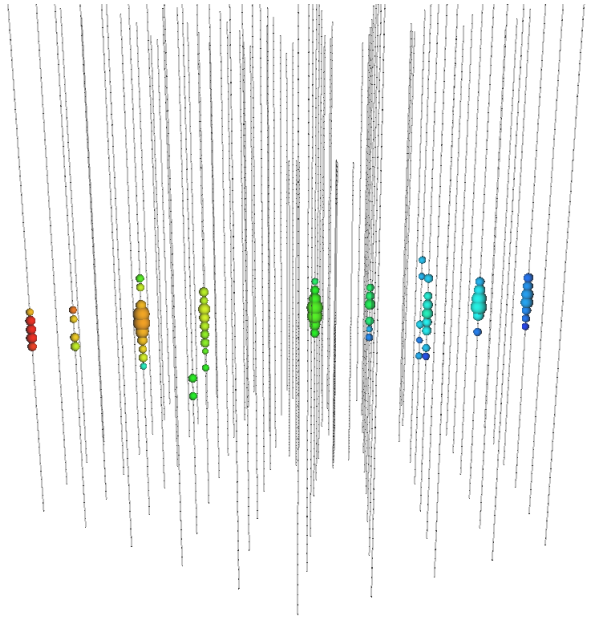
tion running with > 99%
2011

eric μ per second
ν per minute
l ν per day

Event Topologies







(EM / Hadronic) Cascades
Neutral Current (NC) & ν_e (ν_τ) Charged Current (CC)
+ Energy resolution
+ High Purity

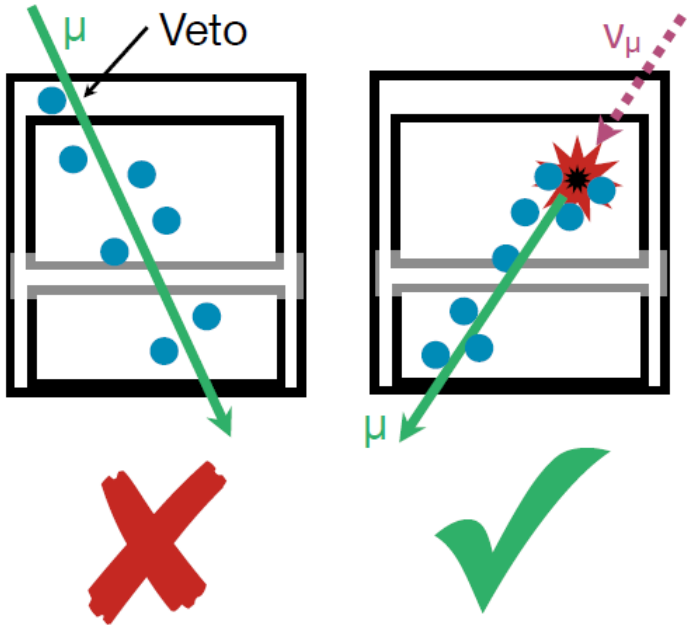
Throughgoing Tracks (muons)
ν_μ CC, atmospheric μ
+ Angular resolution
+ Large effective area

Event Selection Strategies

Fiducialization

Starting Tracks, Cascades

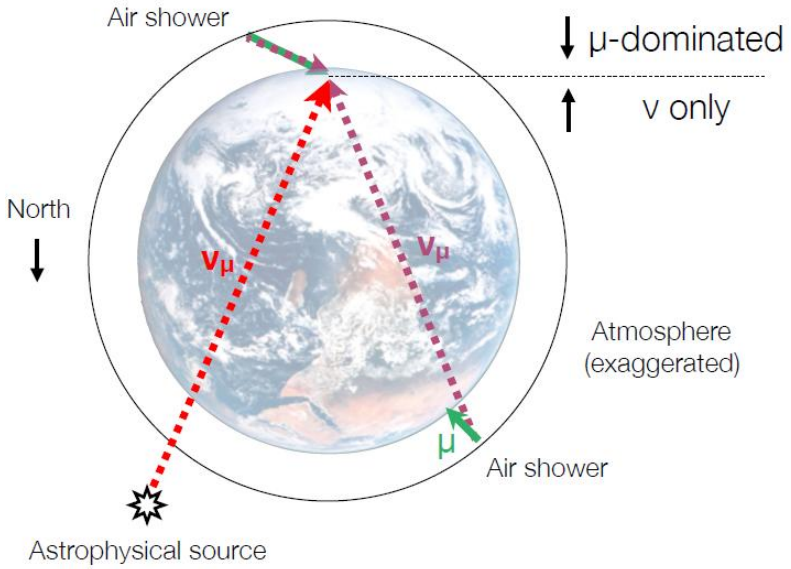
Morphology-based BG discrimination



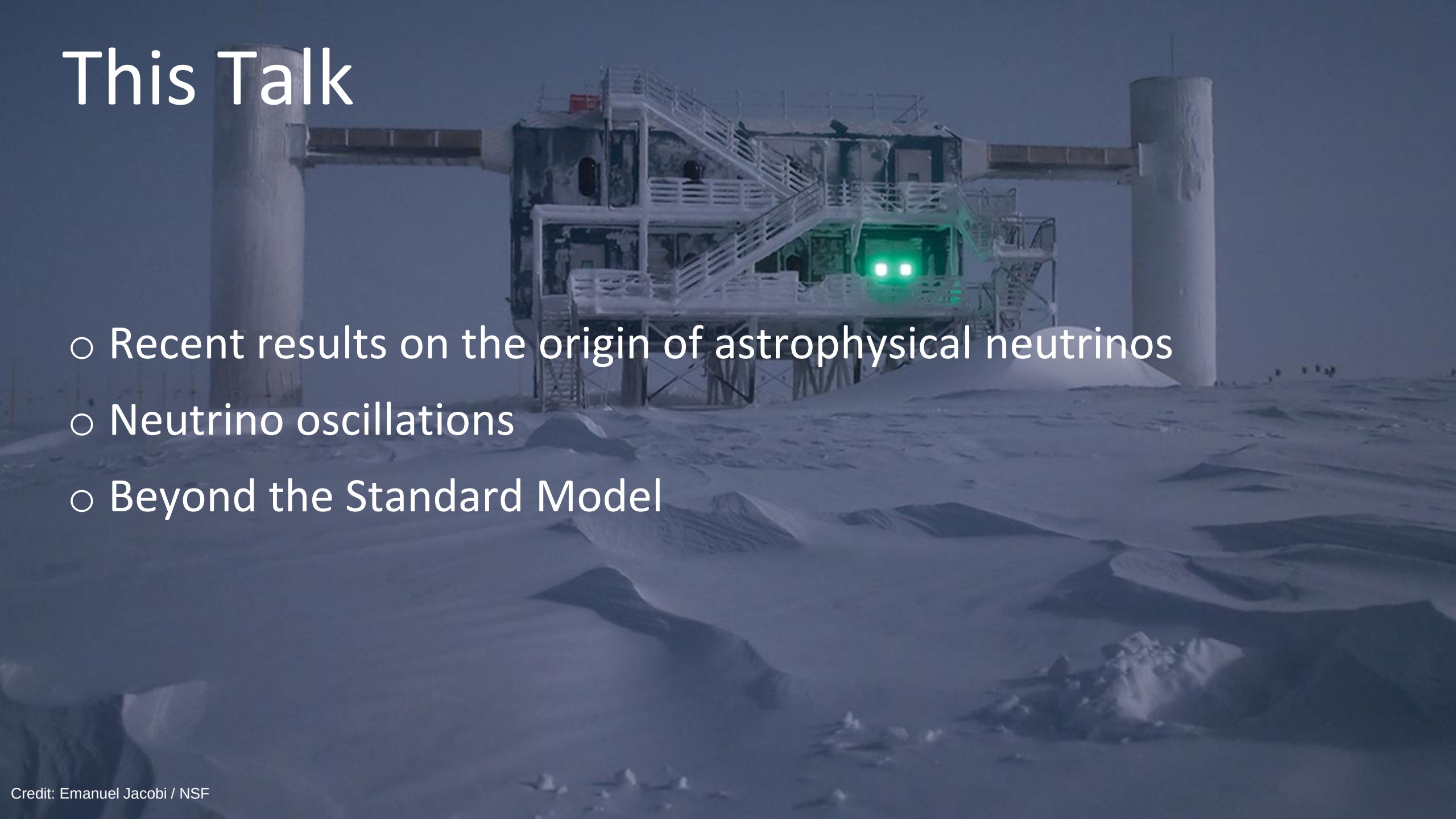
Using Earth as shield

“Upgoing” tracks

Direction based BG discrimination



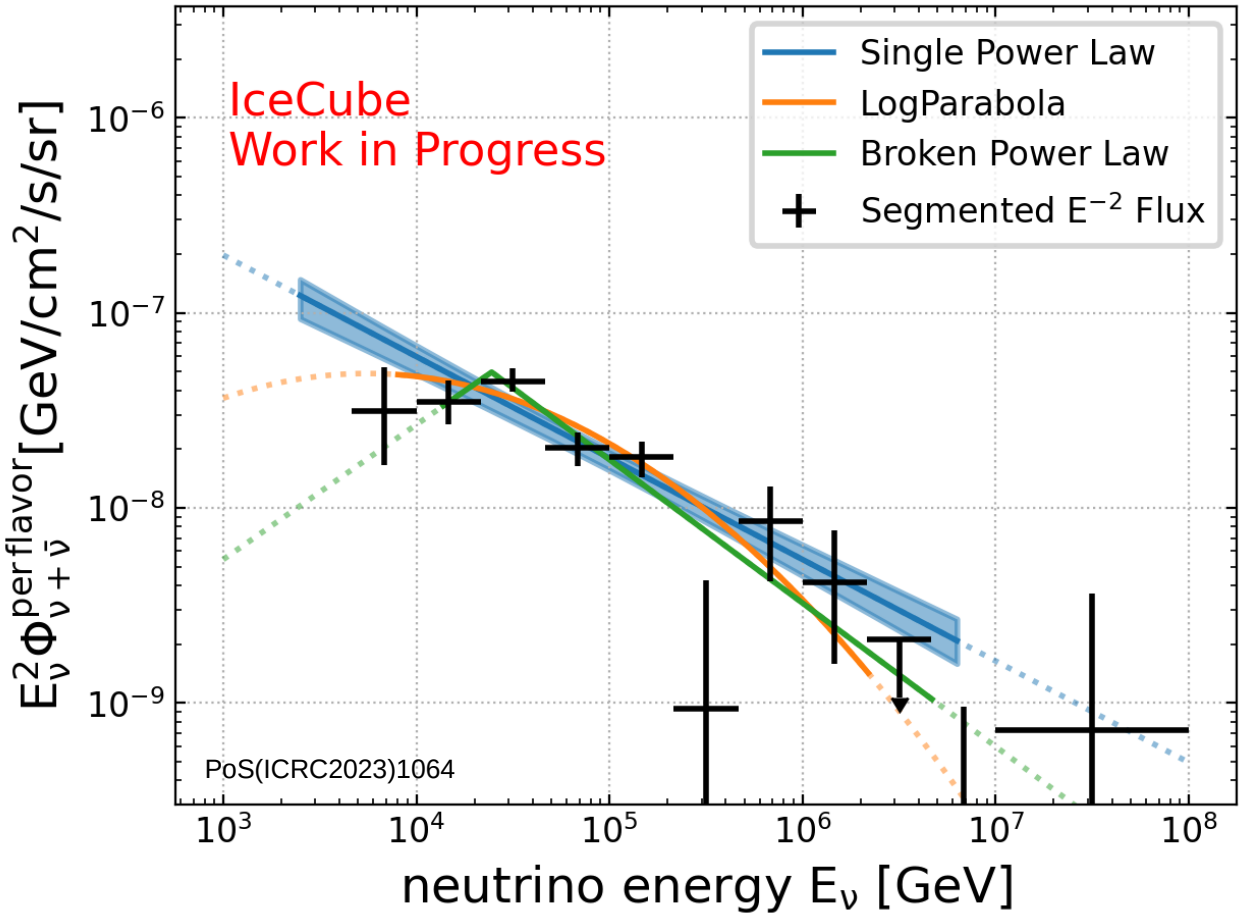
This Talk



- Recent results on the origin of astrophysical neutrinos
- Neutrino oscillations
- Beyond the Standard Model

Credit: Emanuel Jacobi / NSF

Cosmic Neutrino Spectrum



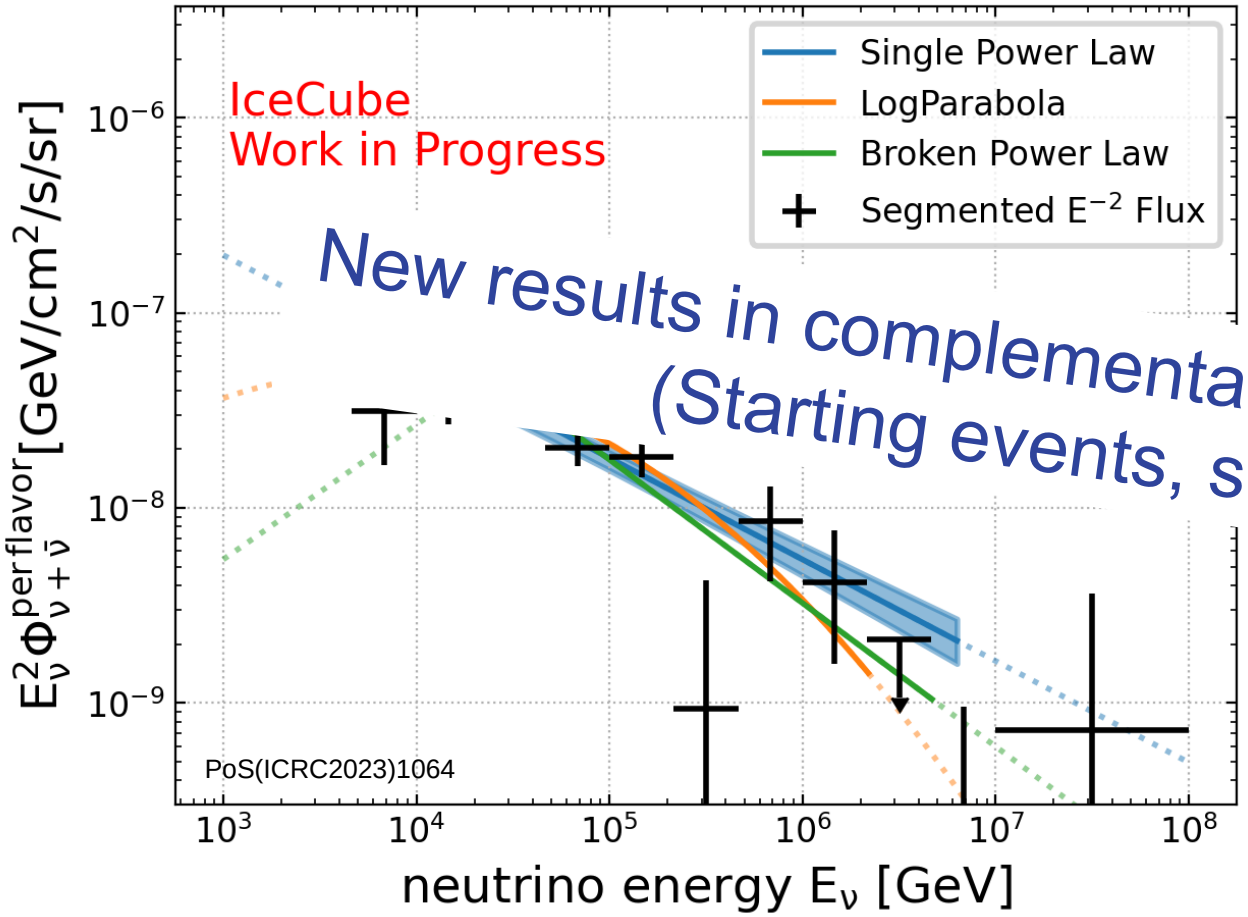
Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

Work in Progress:

- Significance of BPL / LogParabola vs SPL
- Systematic Uncertainties

Cosmic Neutrino Spectrum



Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

- LogParabola vs SPL
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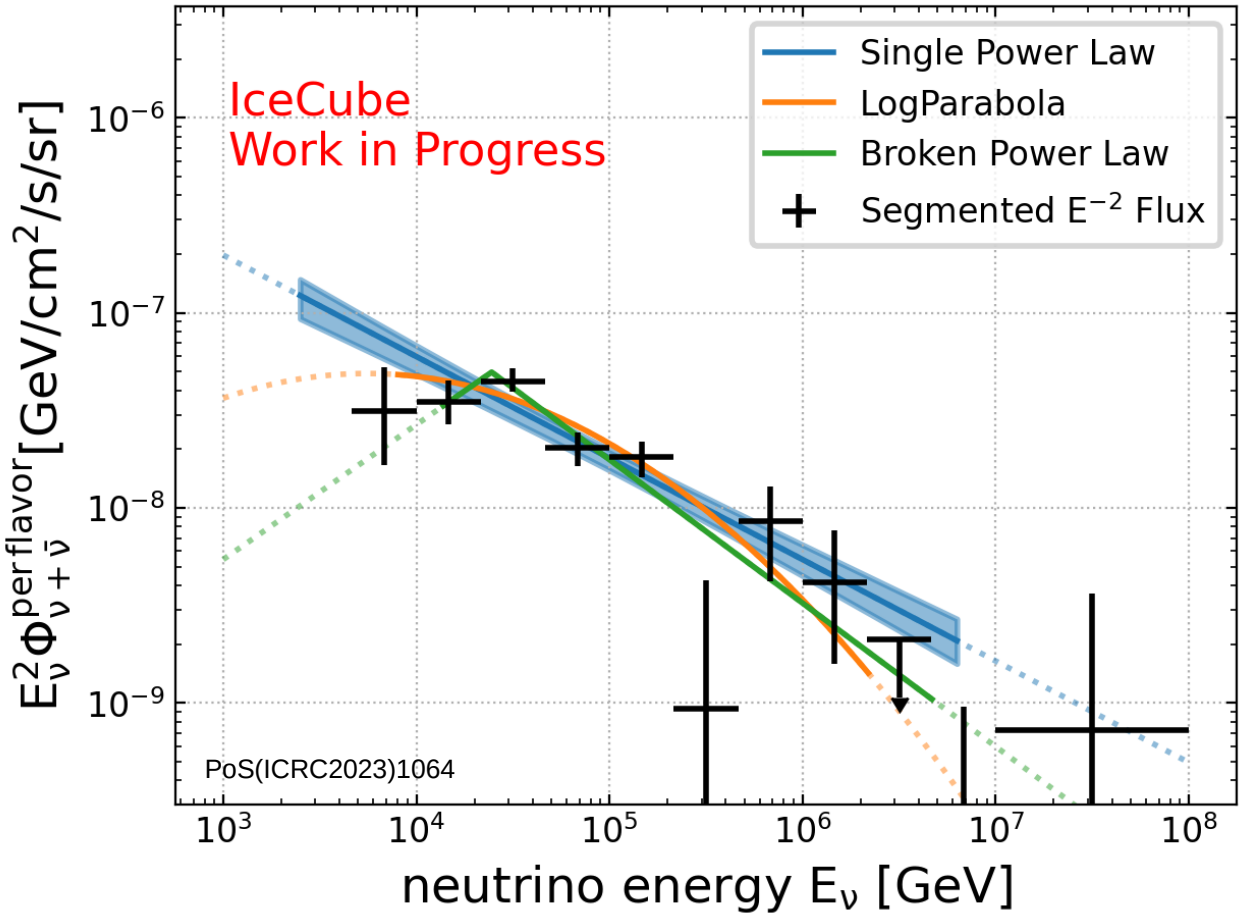
Cosmic Neutrino Spectrum



Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

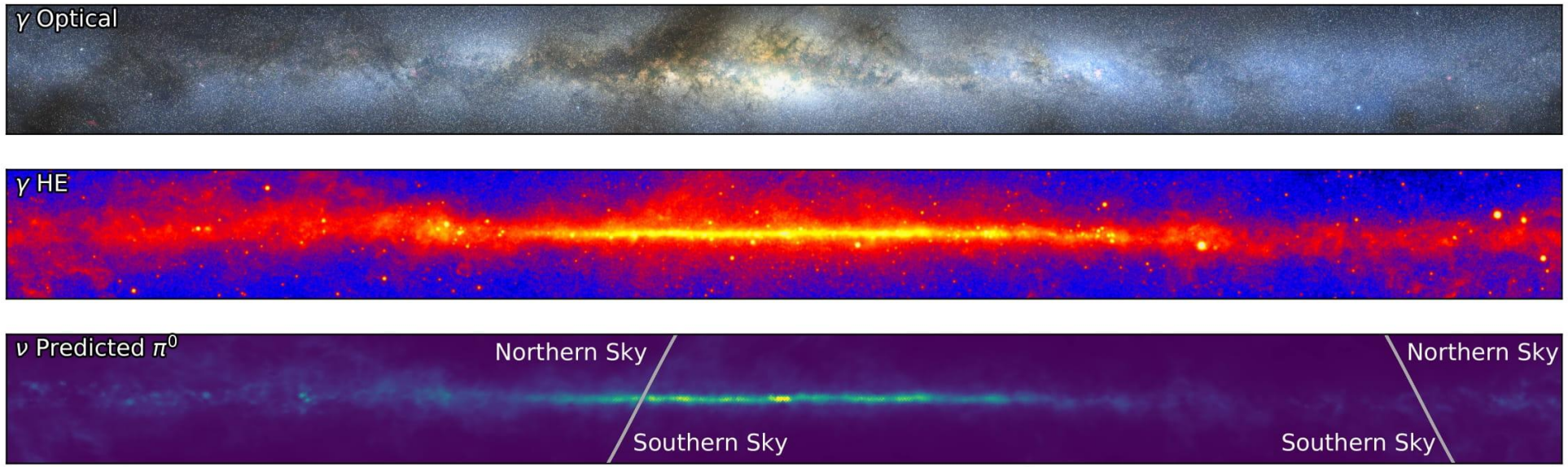
Work in Progress:

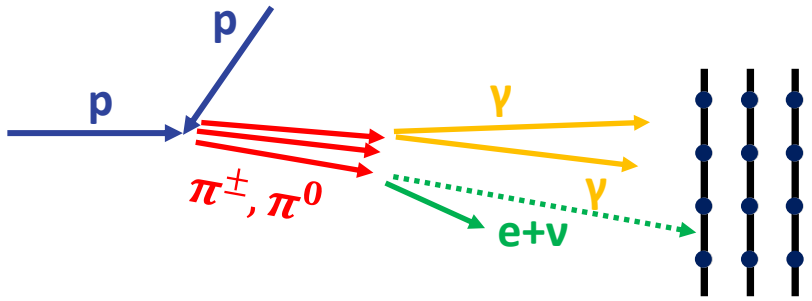
- Significance of BPL / LogParabola vs SPL
- Systematic Uncertainties

What are the sources of these neutrinos?

Neutrinos from the Galactic Plane

DOI: 10.1126/science.adc9818

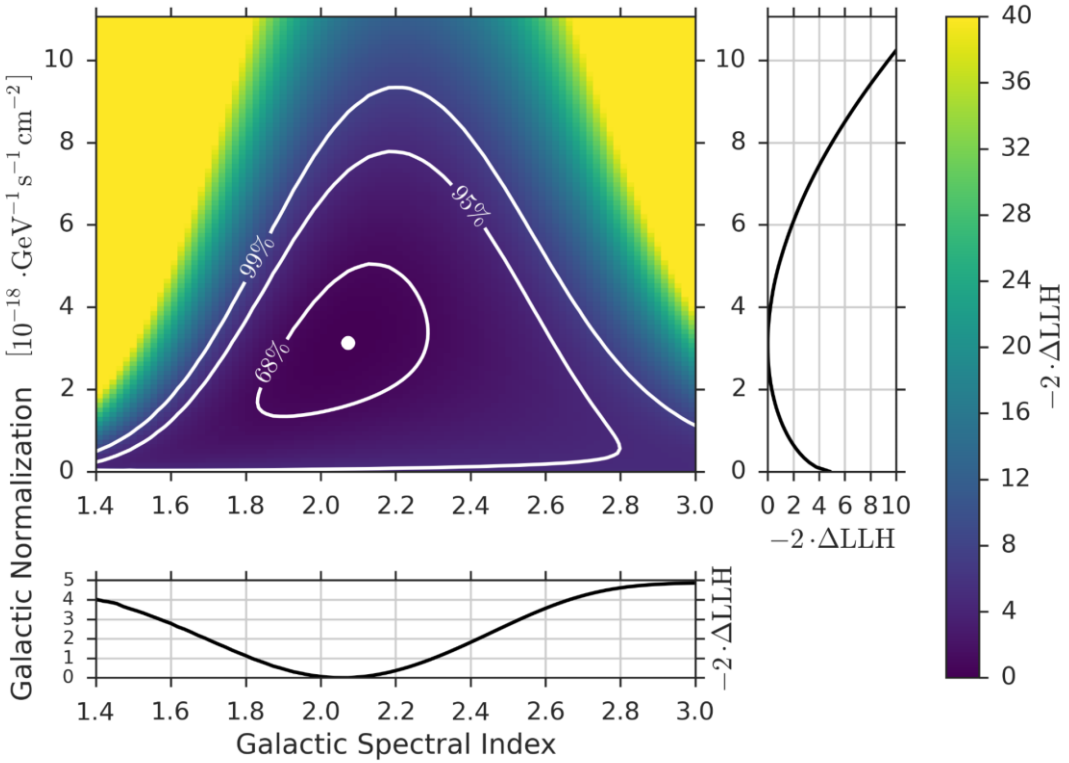




Galactic diffuse neutrino emission is a "guaranteed" flux

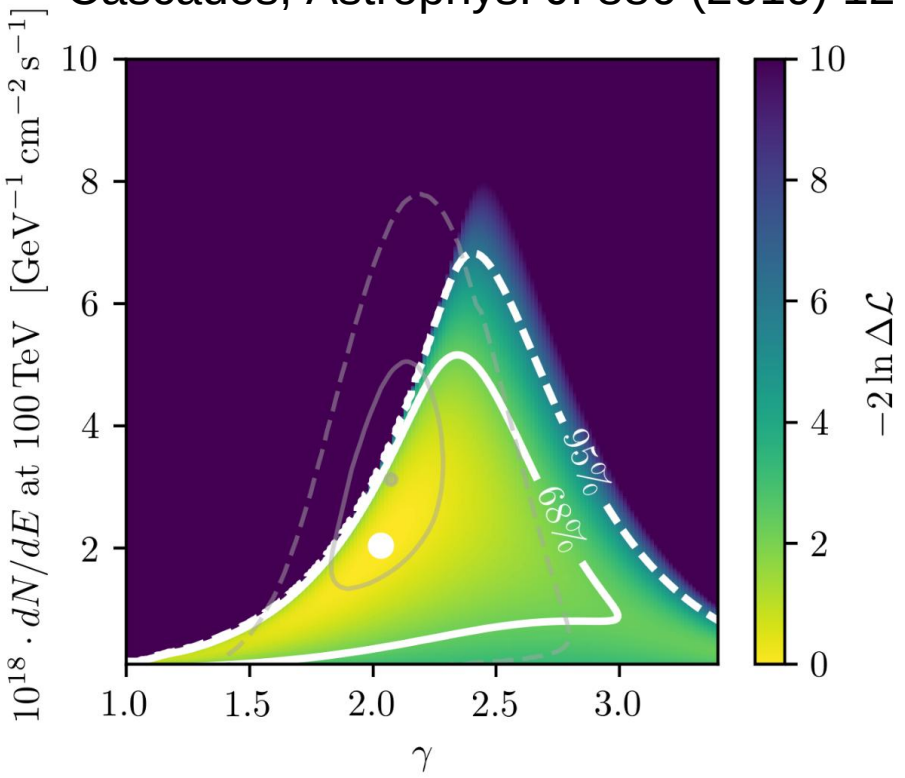
GP Searches in IceCube

Tracks, Astrophys.J. 849 (2017) 67



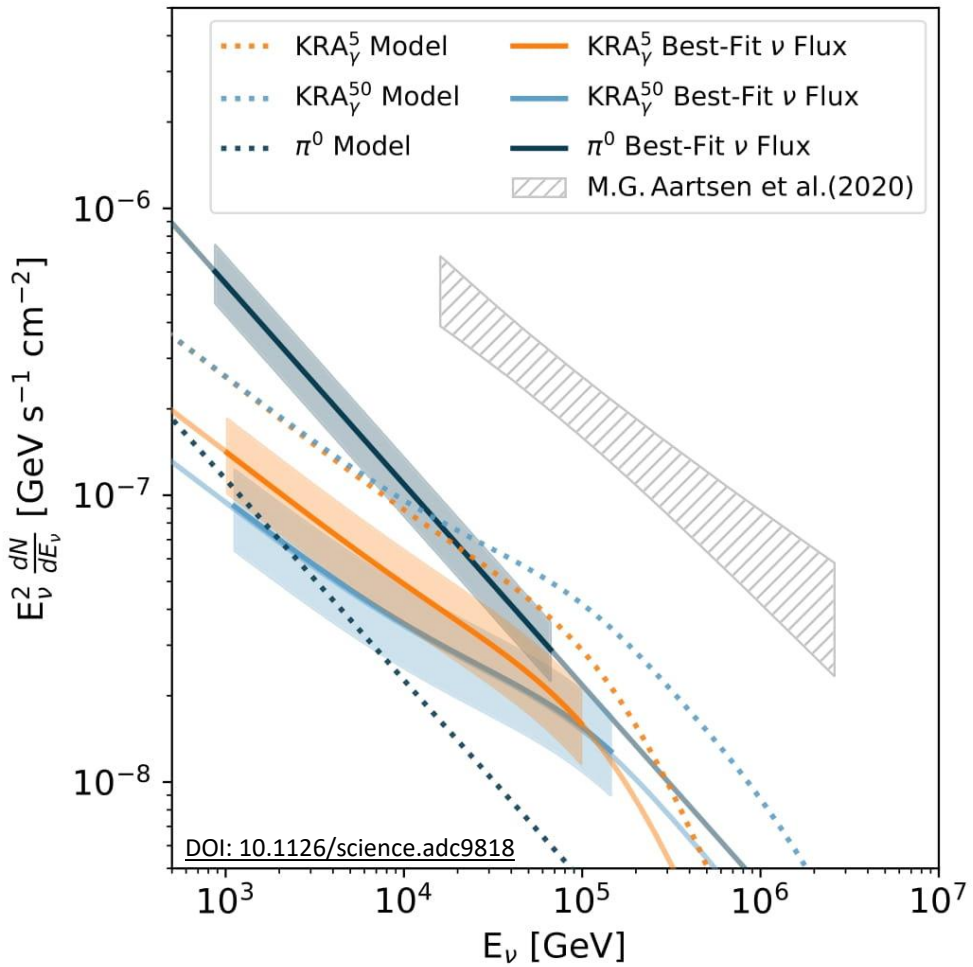
Zero Galactic diffuse excluded @ 7% p-value

Cascades, Astrophys. J. 886 (2019) 12

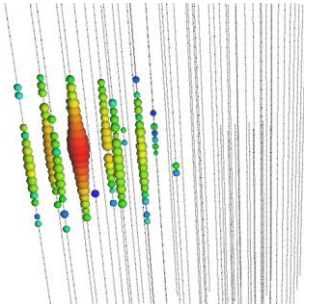


Zero Galactic diffuse excluded @ 2% p-value

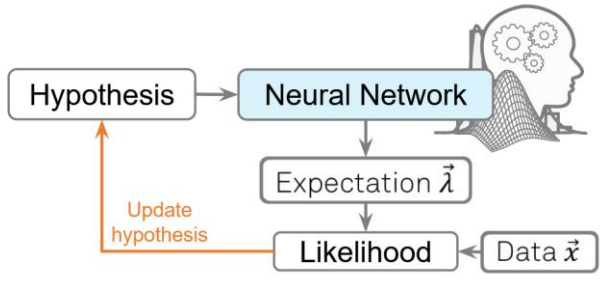
Evidence for Galactic Neutrino Emission



Cascade channel



Deep Learning



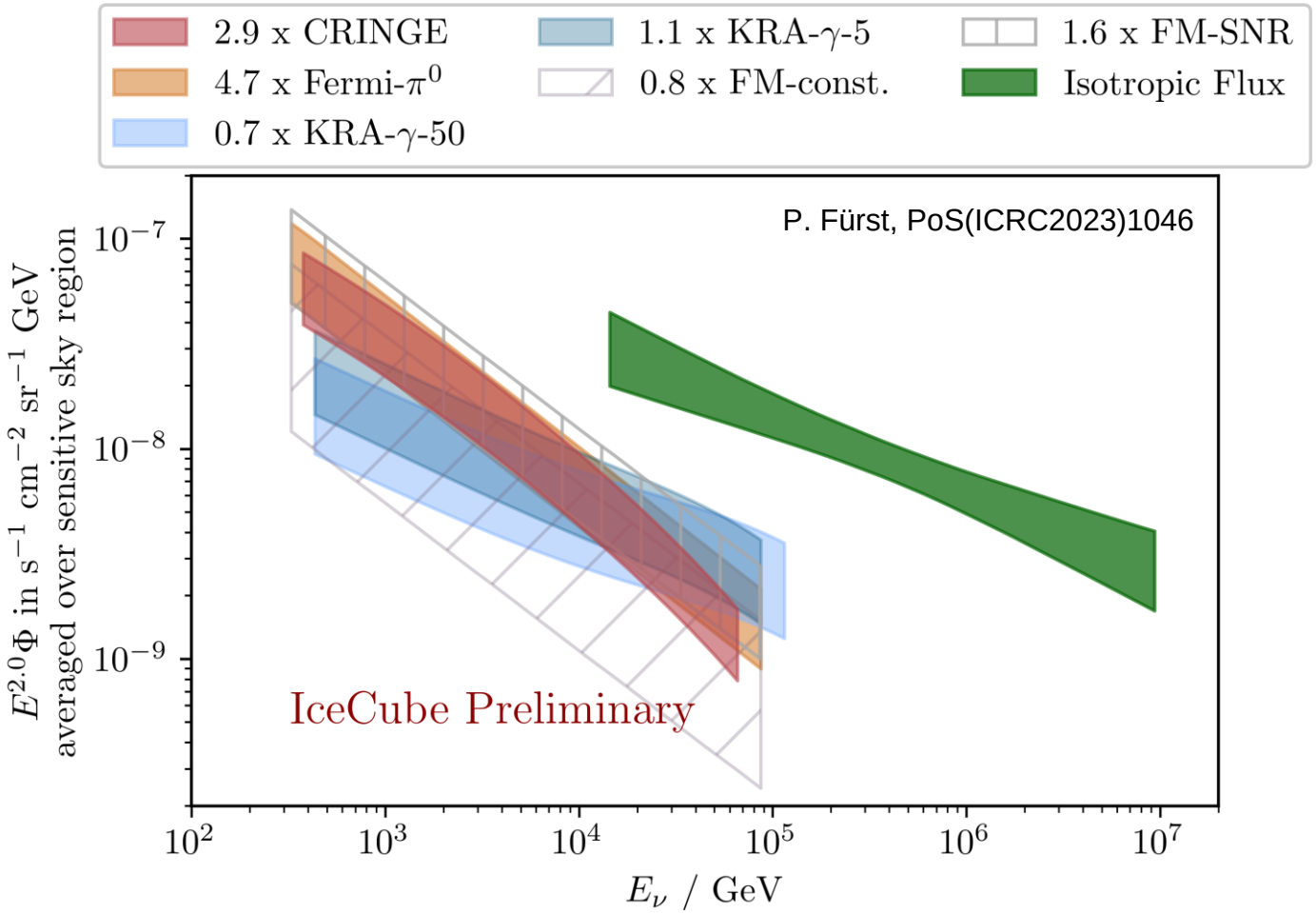
Credit: Mirco Huennefeld

4.5σ exclusion of pure isotropic hypothesis

6-13% of the total diffuse neutrino flux

Not yet enough statistical power to distinguish models or unresolved sources

New Result: Track Channel

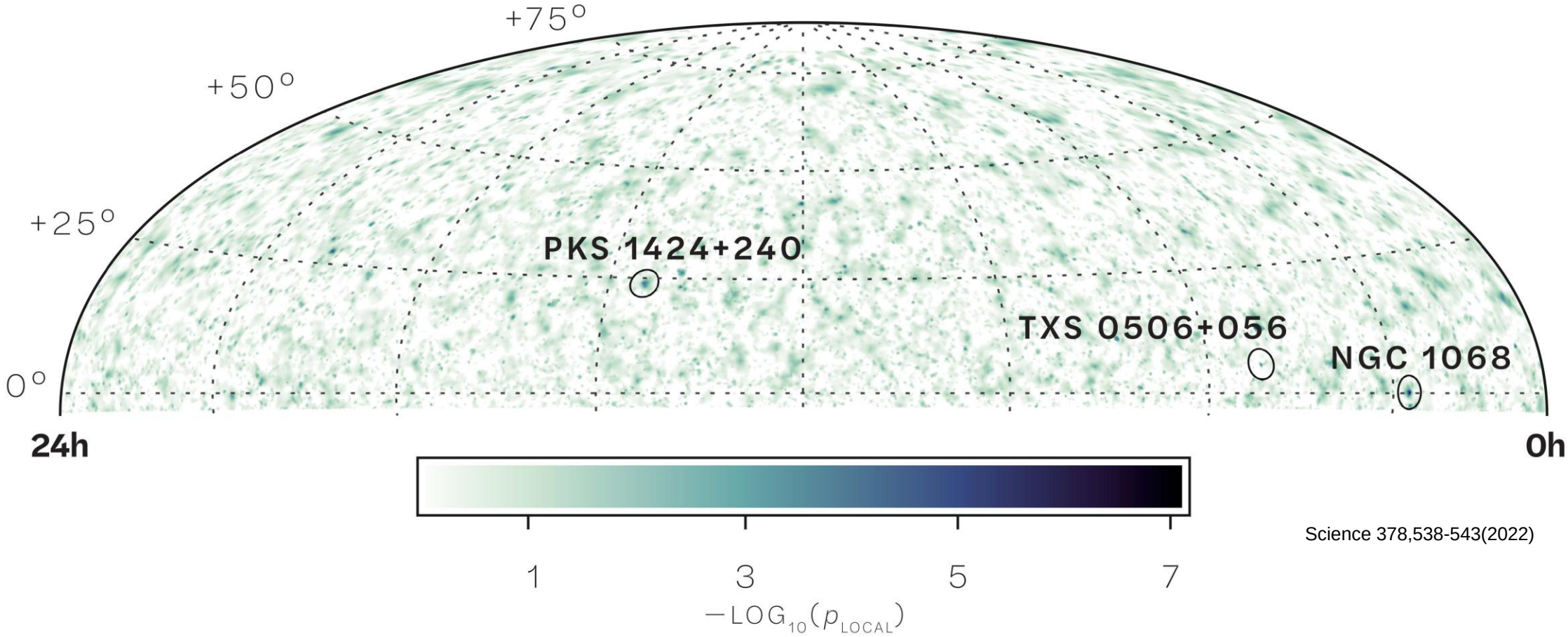


Multiple diffuse emission models tested

Supporting result by independent analysis using track channel (2.7σ)

The Muon-Neutrino Sky

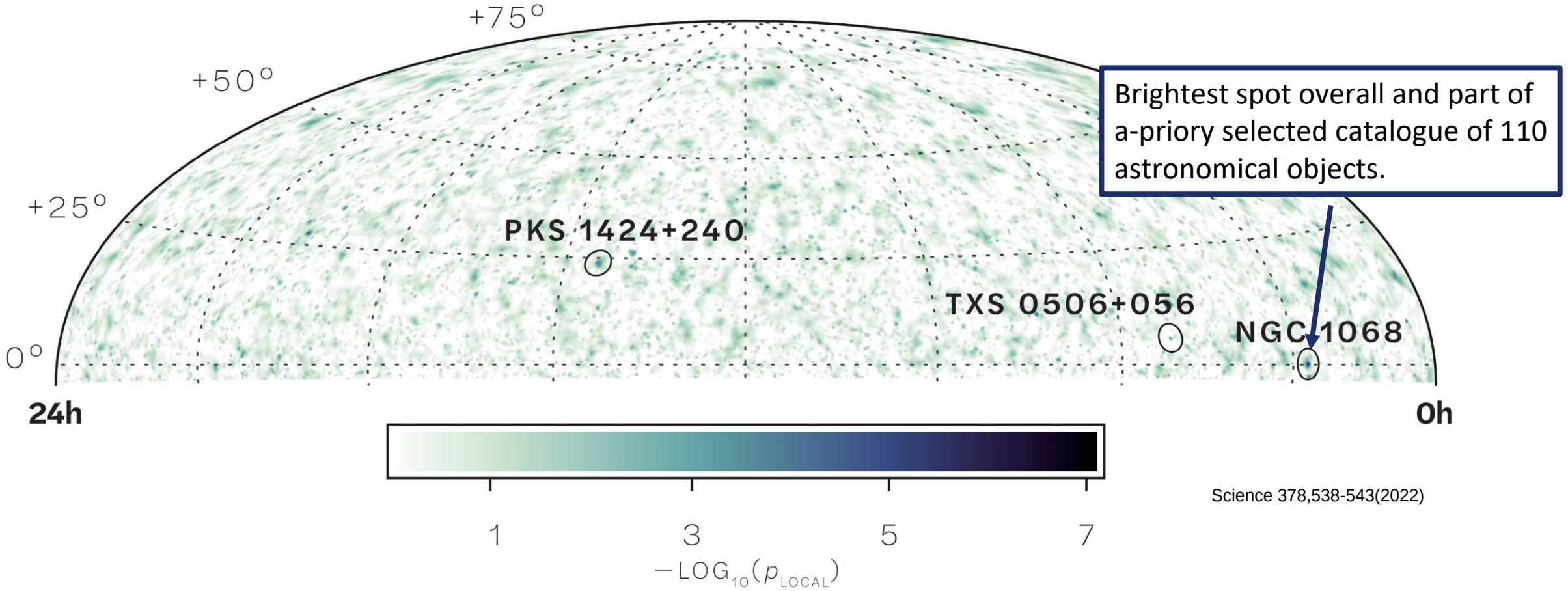
Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky



Science 378,538-543(2022)

The Muon-Neutrino Sky

Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky



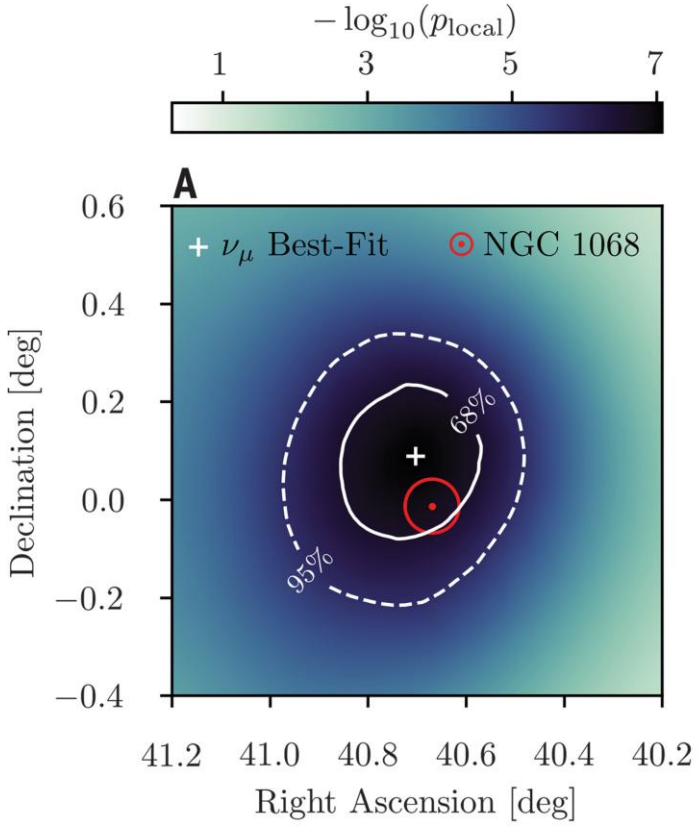
Brightest spot overall and part of a-priory selected catalogue of 110 astronomical objects.

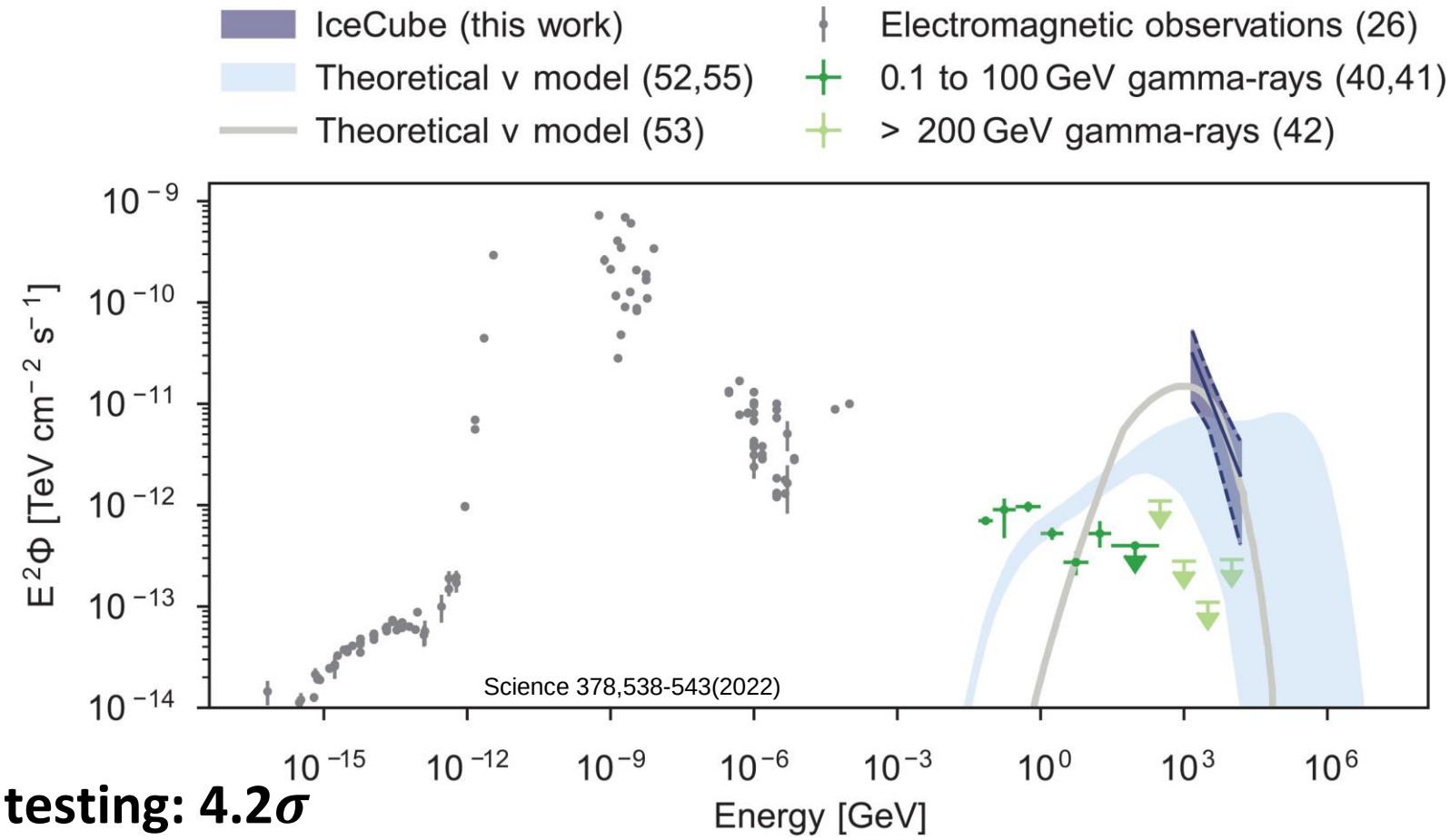
Science 378,538-543(2022)

NGC1068

- Type II Seyfert Galaxy
- d=14.4Mpc
- Compton-thick AGN
- Intrinsic X-ray photons in corona can provide target for ν production

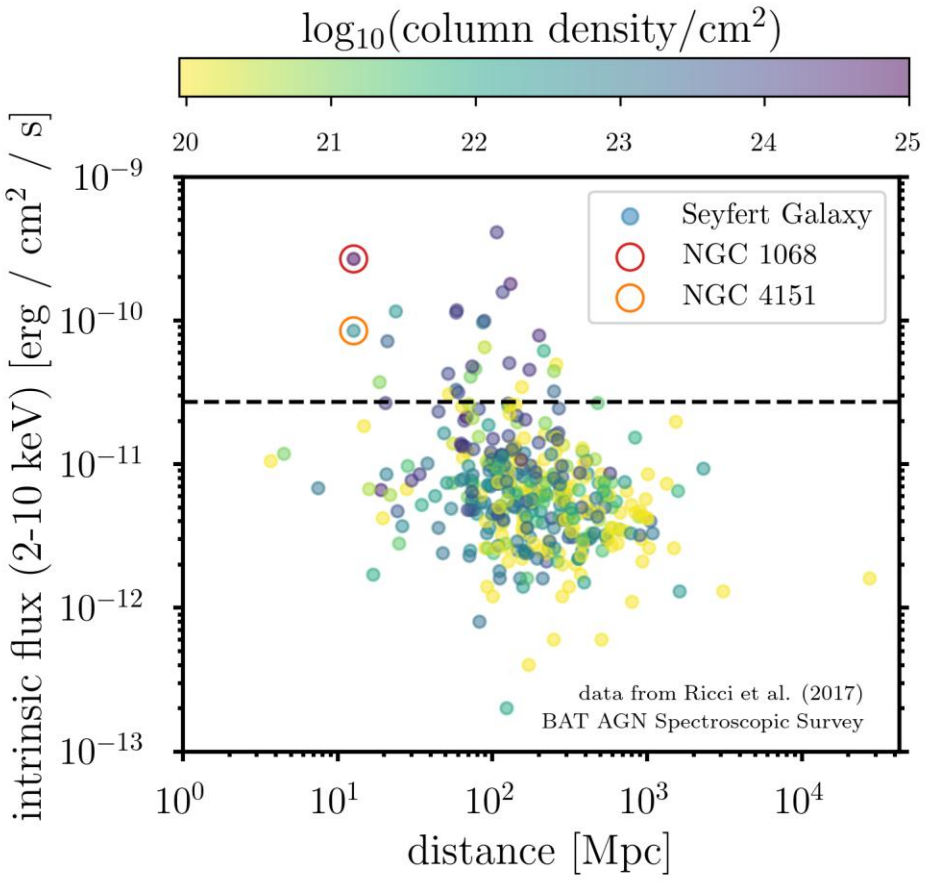
Neutrino Emission from NGC1068





After correction for multiple testing: 4.2σ

Seyfert Galaxies



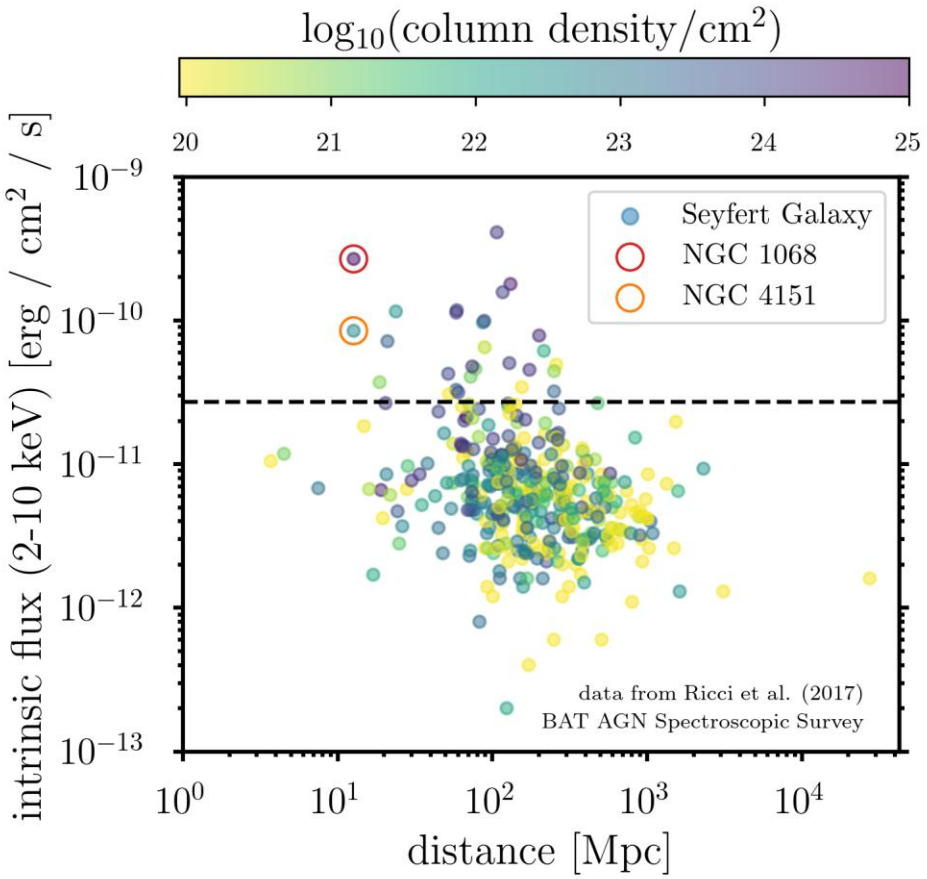
Searching for ν emission from Seyfert galaxies

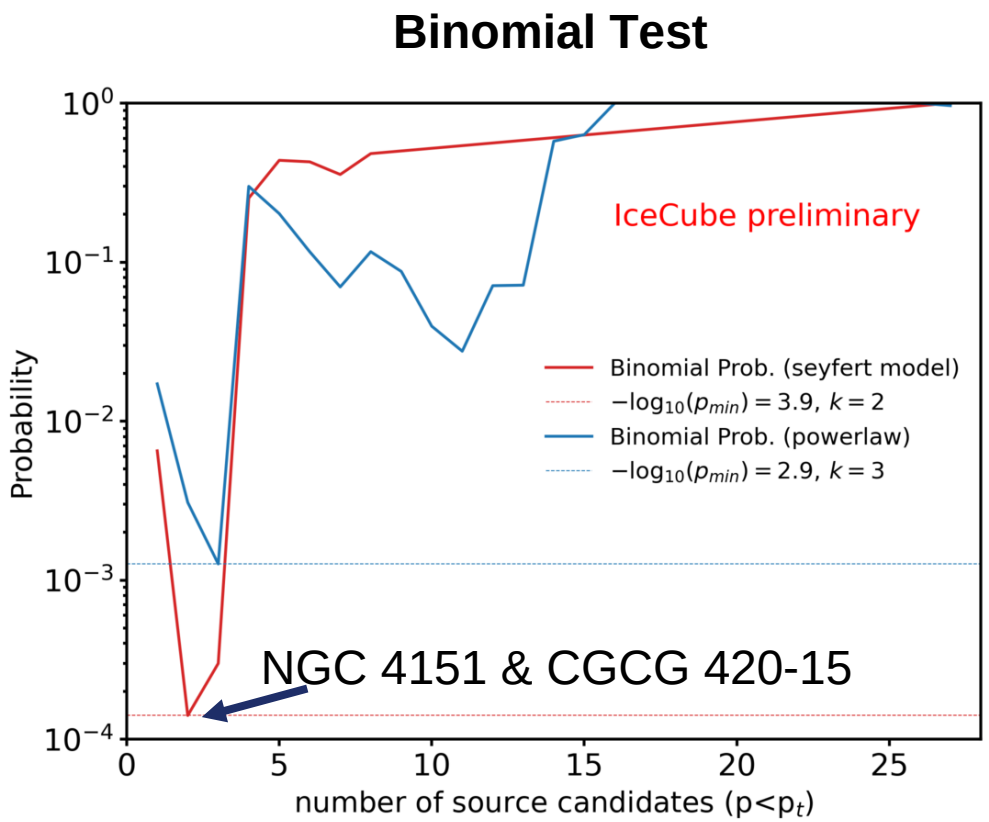
Multiple tests:

- Individual sources (significant emission from single source in catalogue)
- Stacking (combined emission of source catalogue)
- Binomial test: Prob. of finding k sources with $p < p_t$

NGC1068 not included in significance calculation!

Seyfert Galaxies

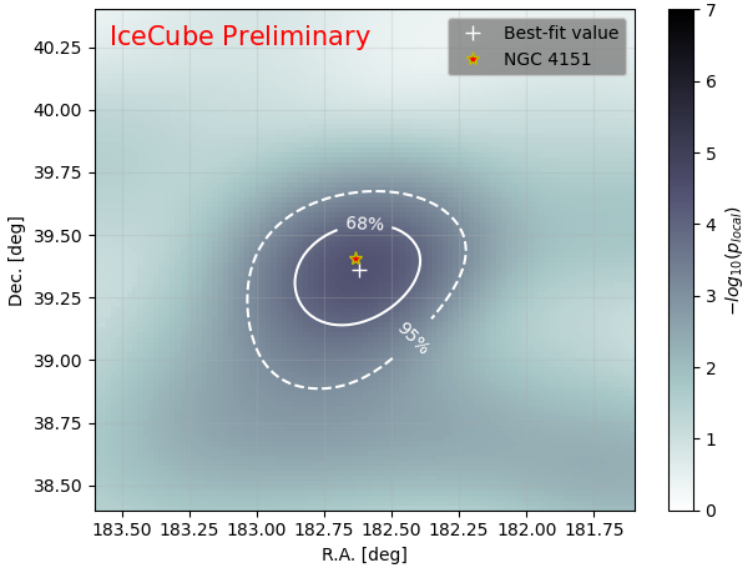




After correcting for multiple testing: 2.7σ excess

Seyfert Galaxies

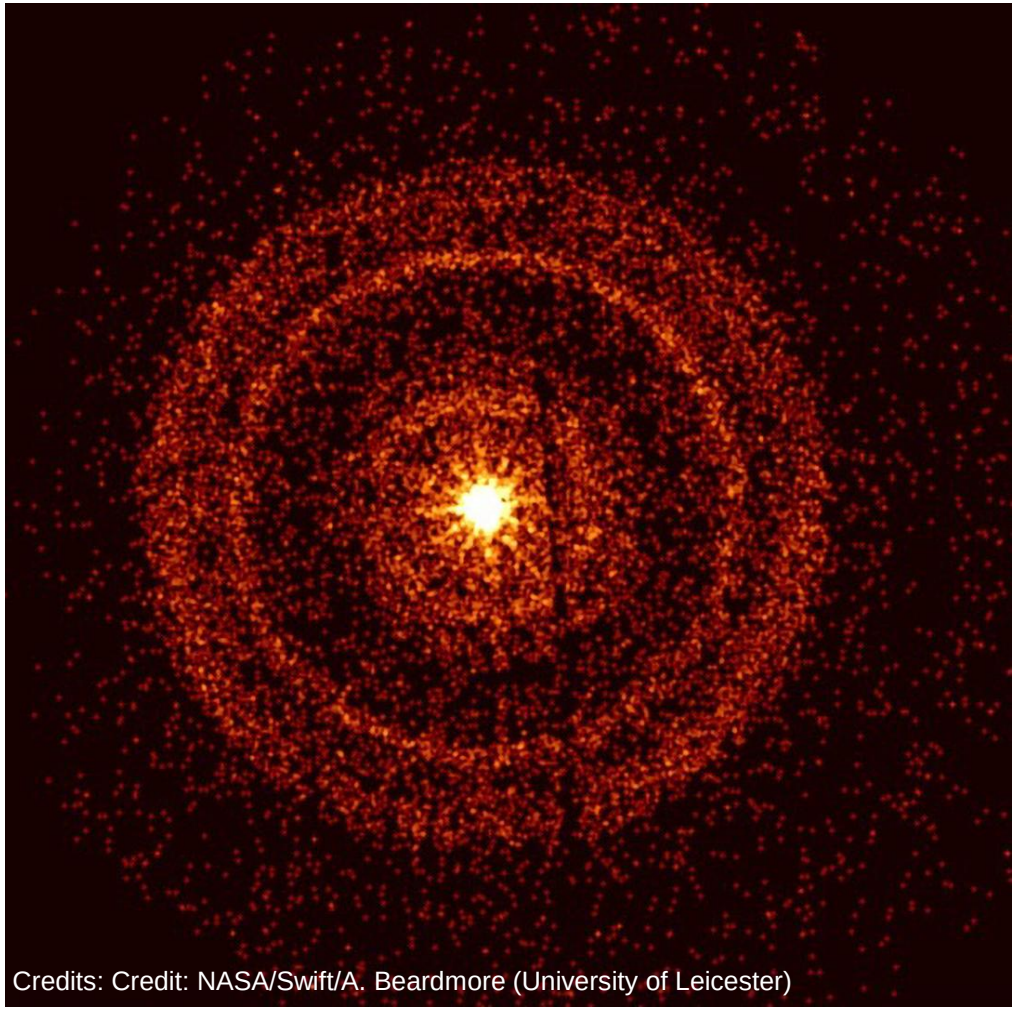
NGC4151

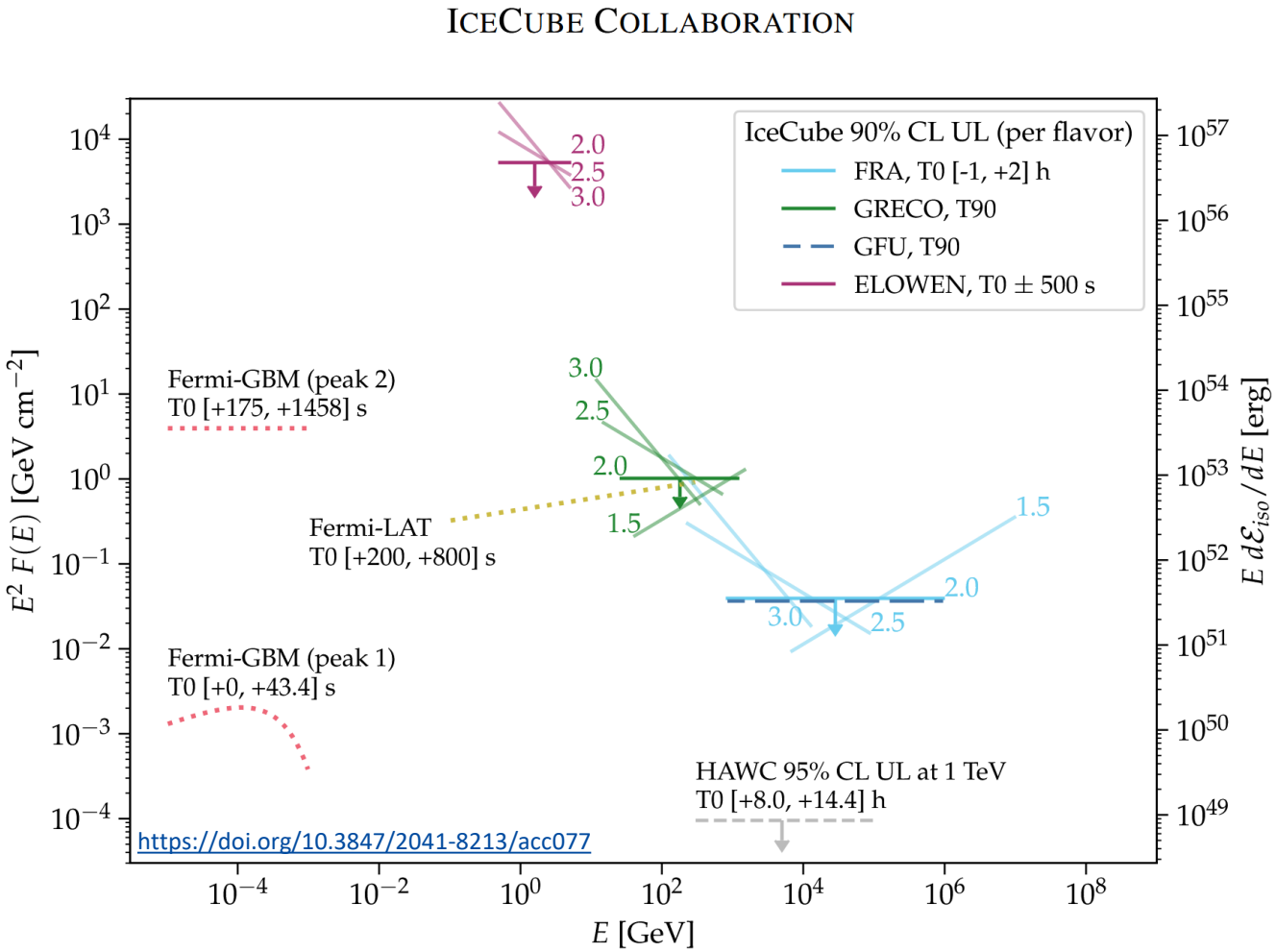


Independent (but overlapping) analysis searching for ν emission from hard X-ray sources: **2.9σ**

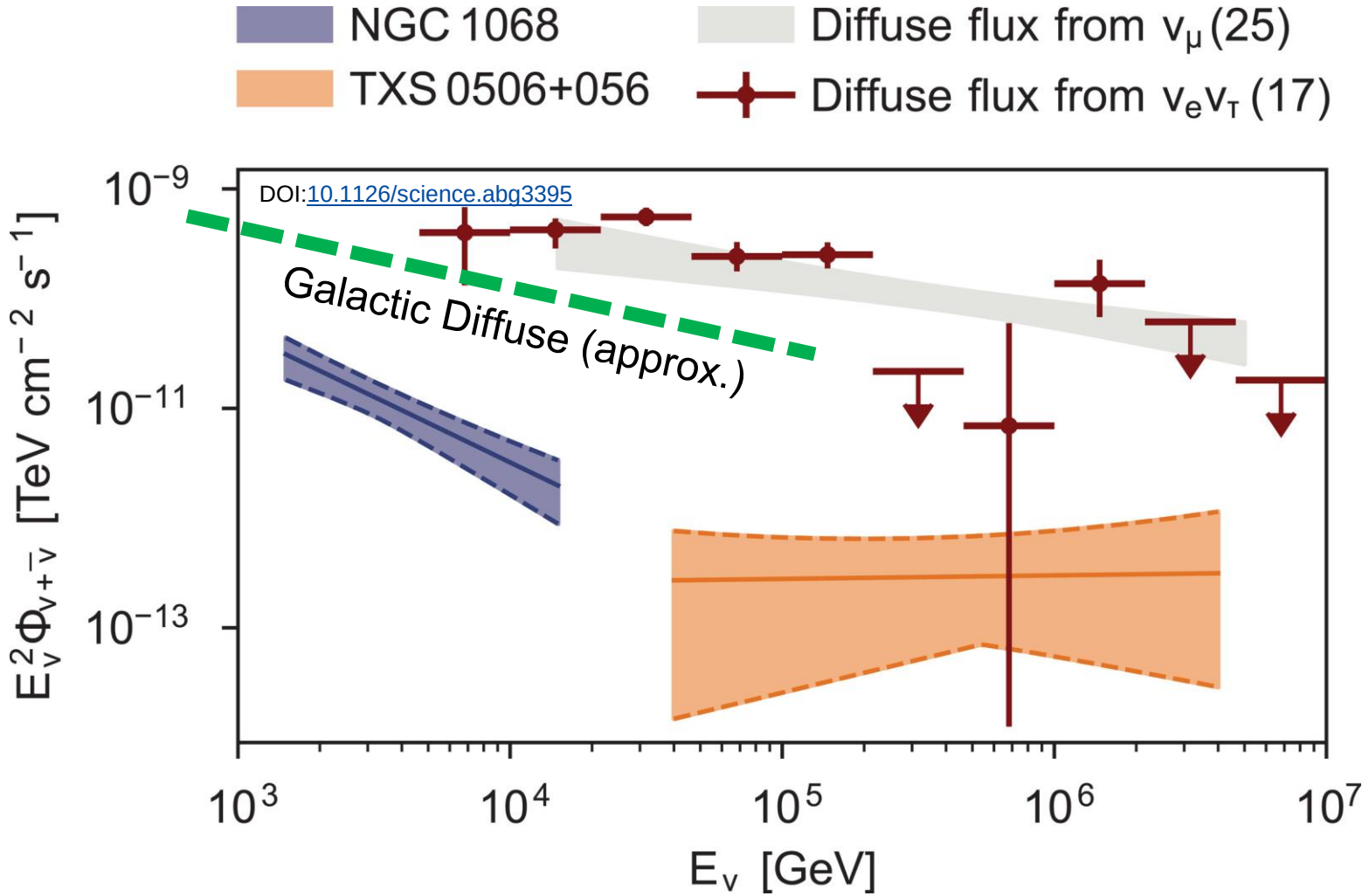
σ excess

GRB221009A


Credits: Credit: NASA/Swift/A. Beardmore (University of Leicester)

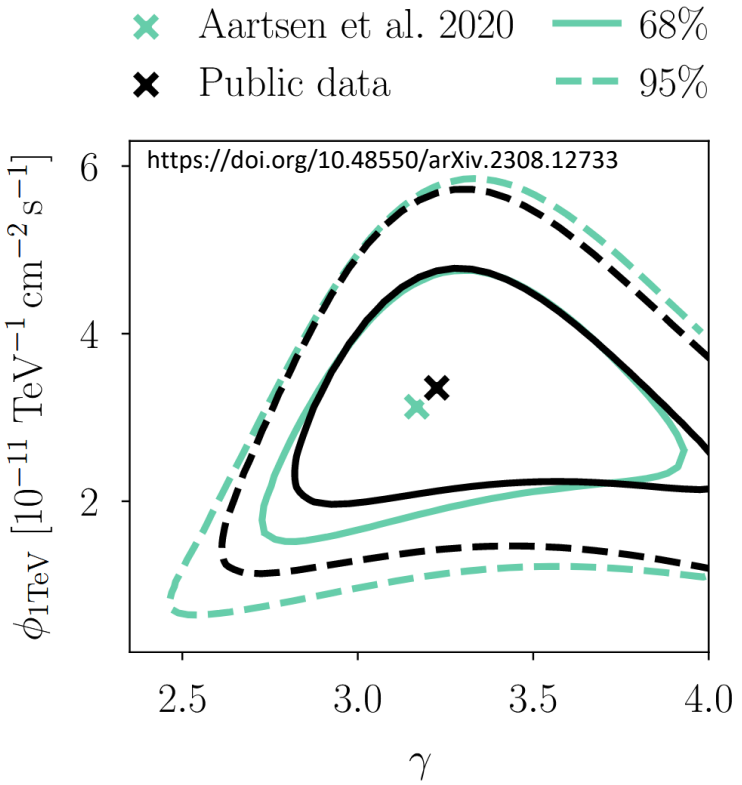


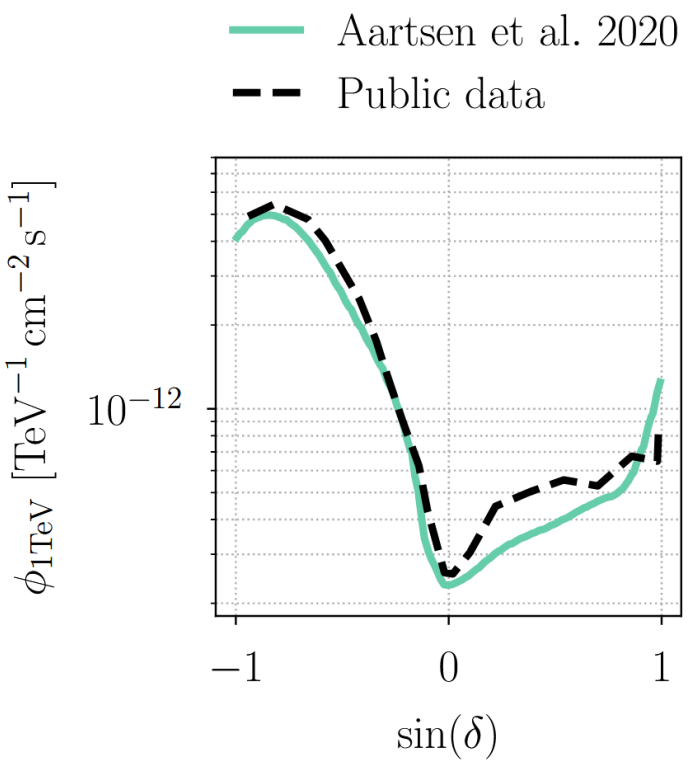
Neutrino Fluxes



IceCube Public Data & Software

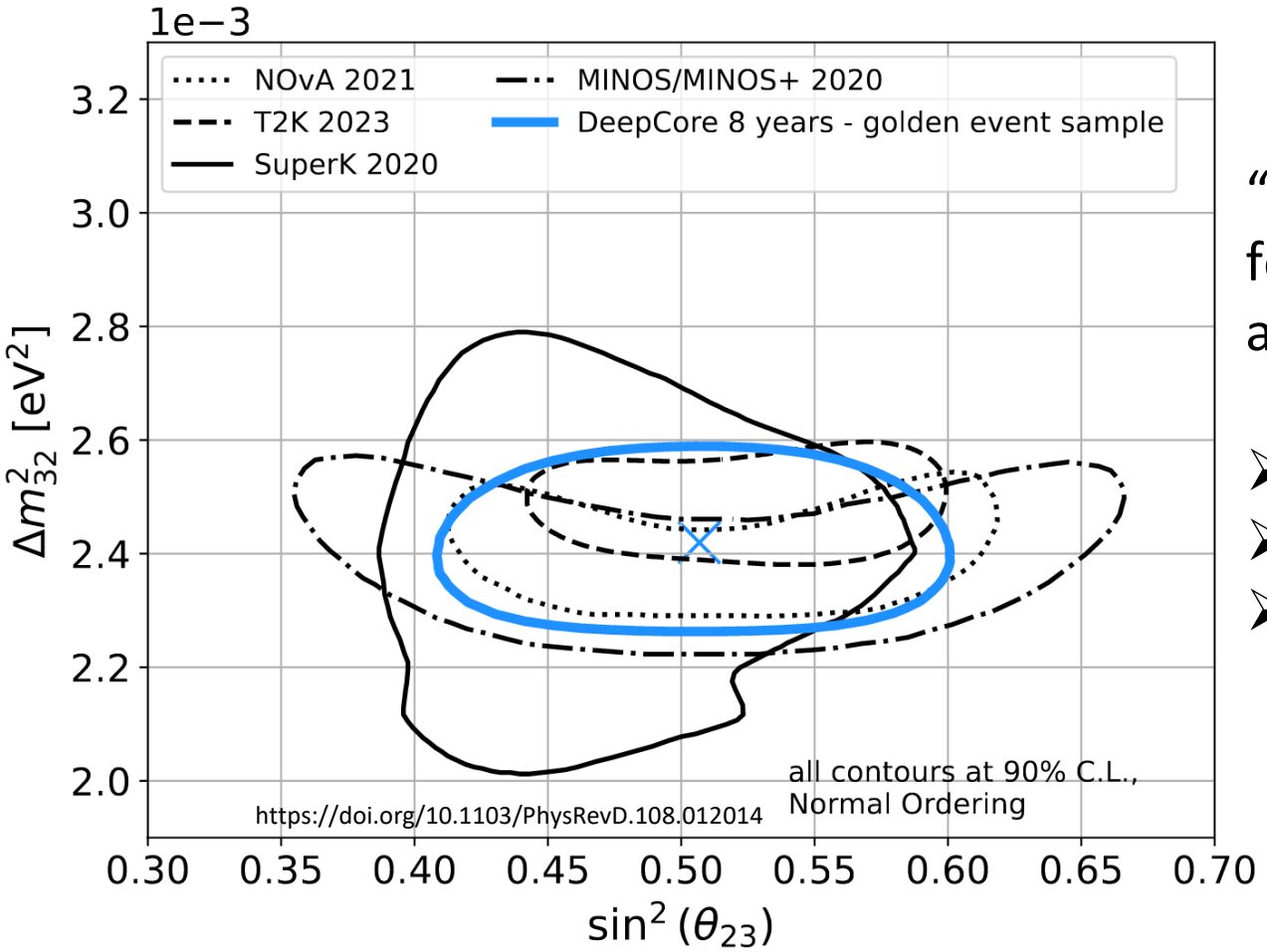
https://github.com/icecube/skyllh
https://arxiv.org/abs/2101.09836





- Public data & software for performing various astrophysical searches
- Obtained sensitivities comparable to internal software / data

Neutrino Oscillations

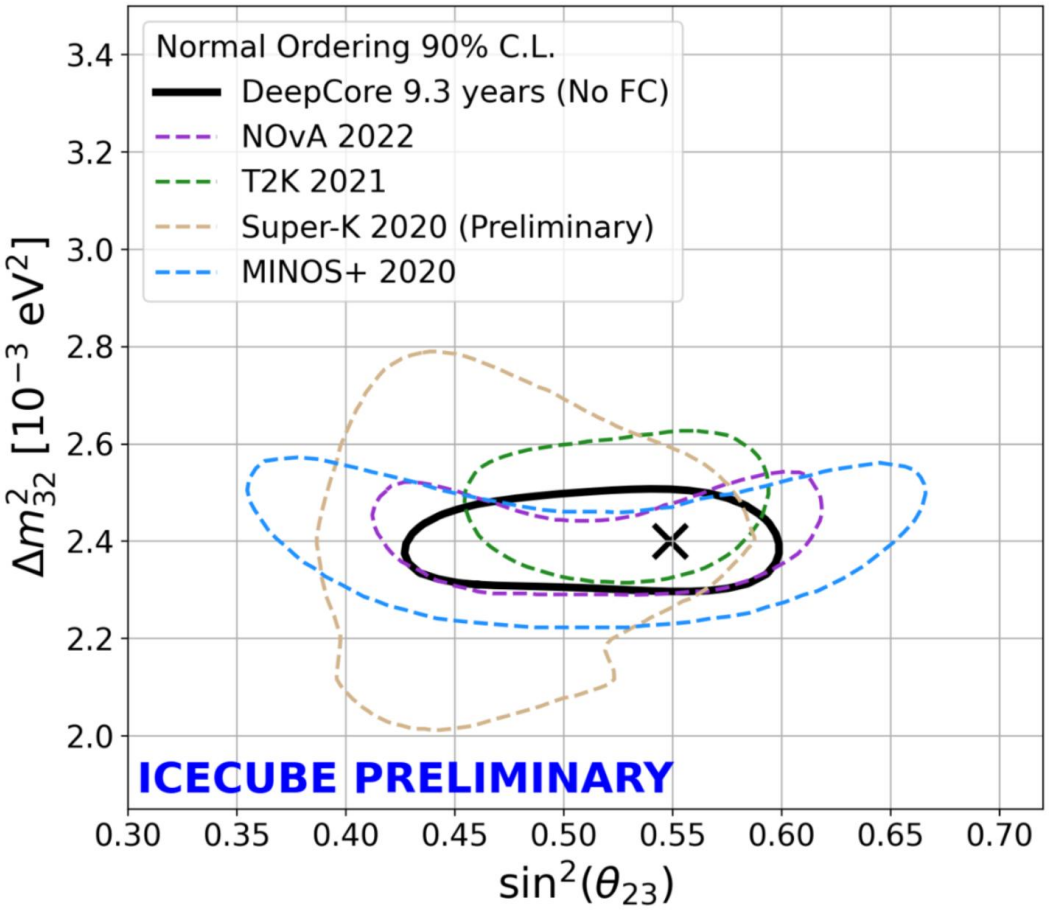


"OscNext": Large multi-year effort to lay foundation for next-generation neutrino oscillation analyses in IceCube

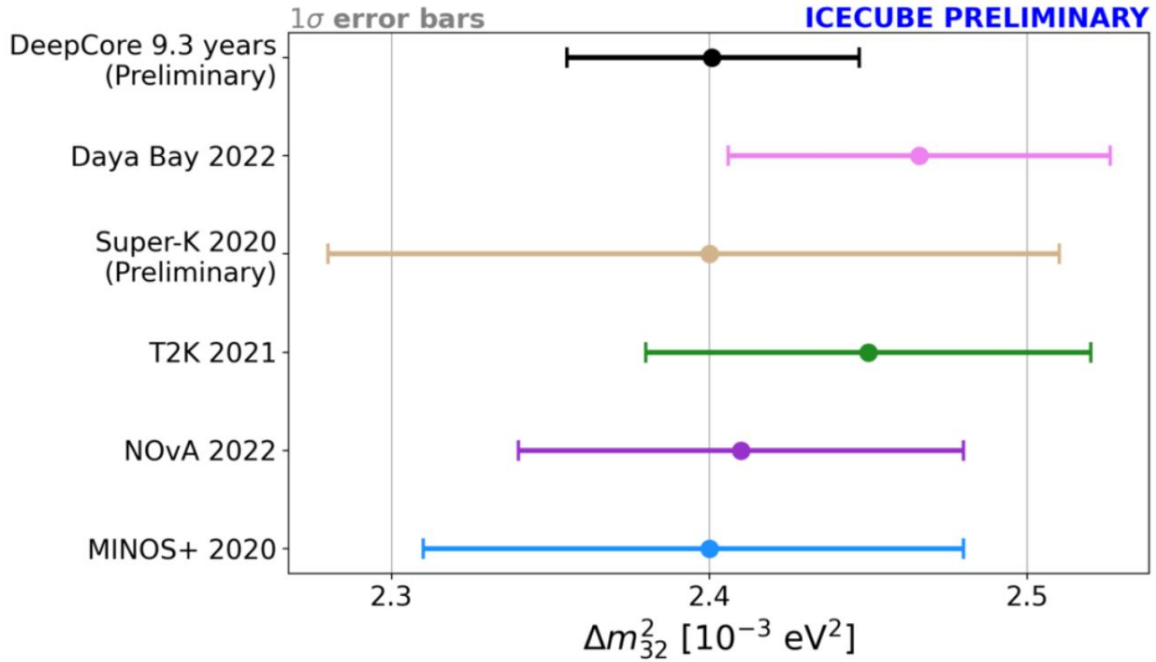
- Improved calibration & filtering
- Improved reconstructions
- Improved treatment of systematic uncertainties

Neutrino Oscillations

https://doi.org/10.48550/arXiv.2307.15855



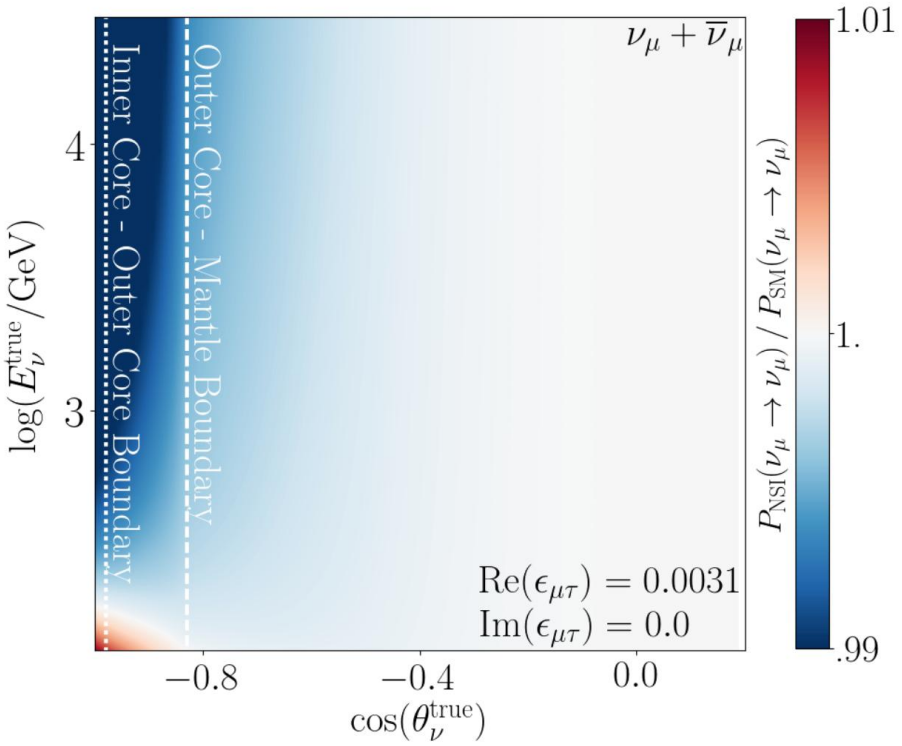
Using CNN for event reconstruction & PID

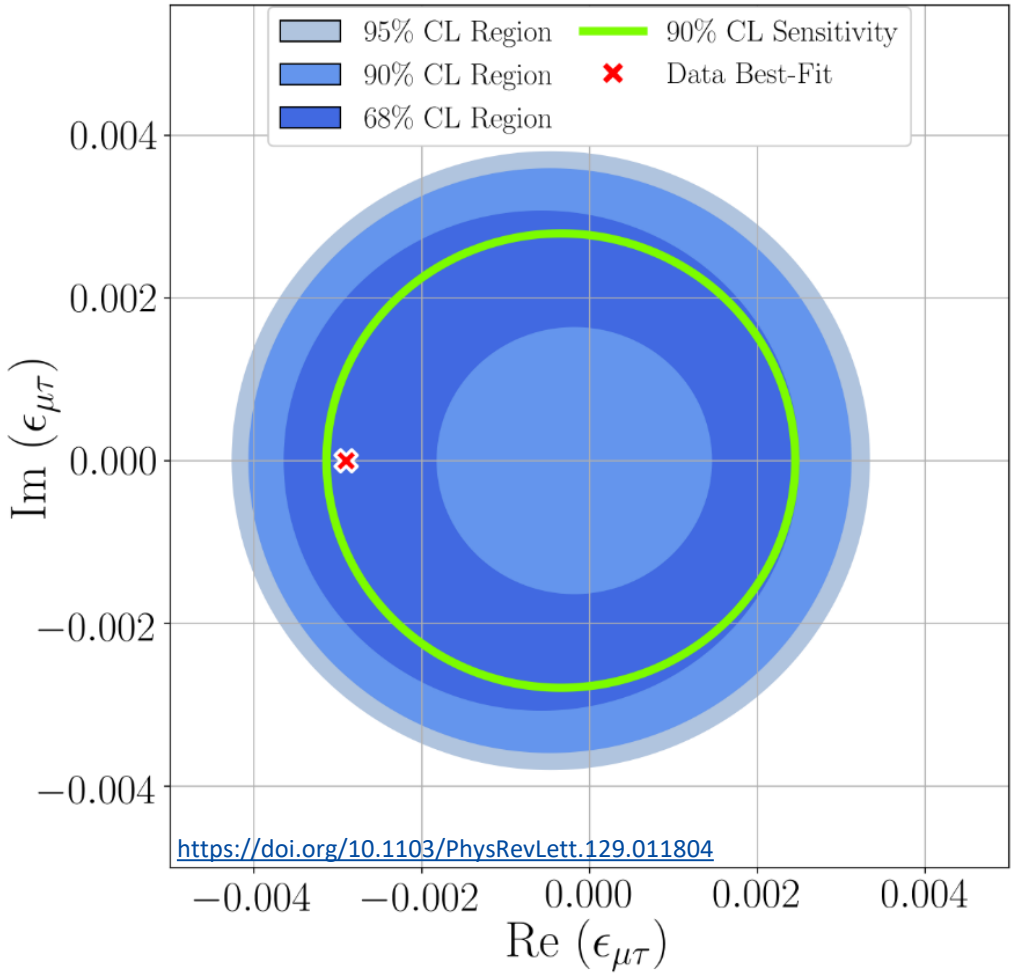


Non-Standard Interactions

CC-Scattering Hamiltonian

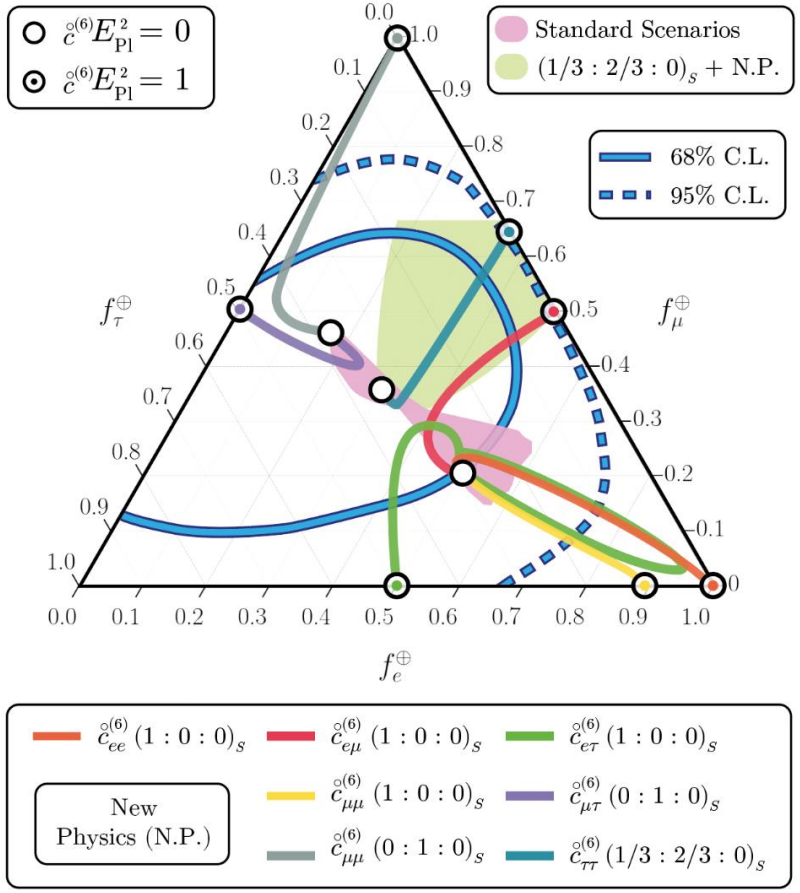
$$H_{\text{mat+NSI}} = V_{CC}(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

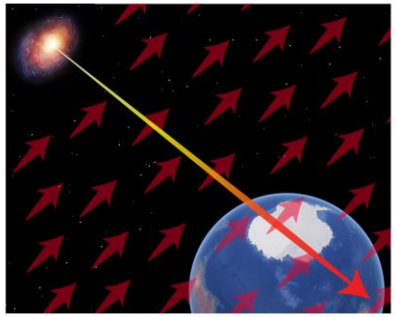




Quantum Gravity

https://doi.org/10.1038/s41567-022-01762-1





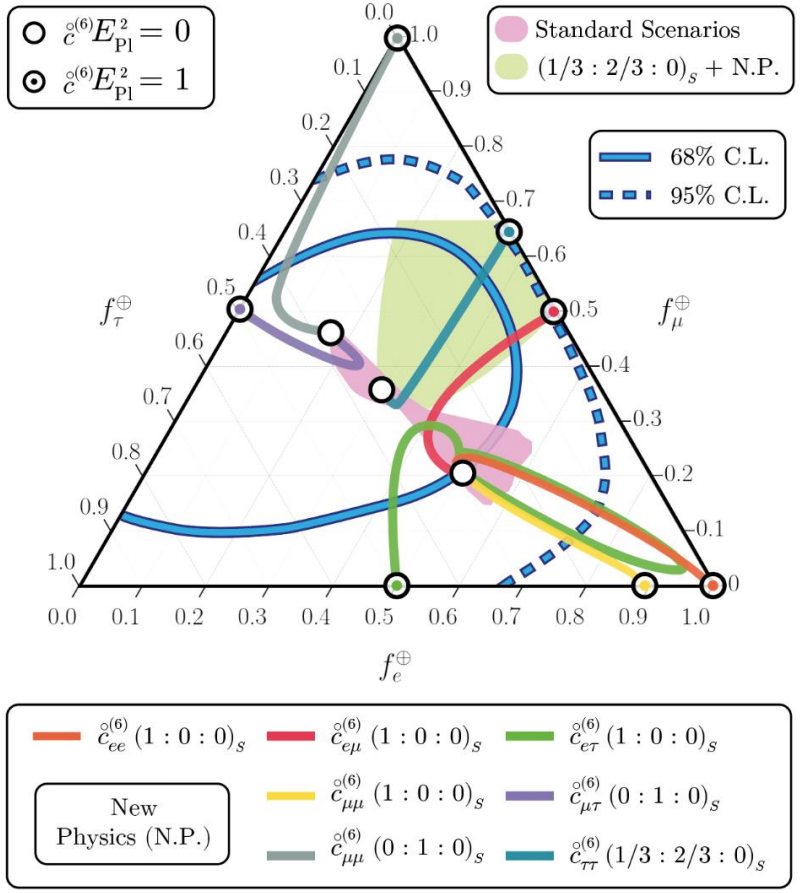
Idea: Neutrino propagation over cosmic distance scales is influenced by space-time defects

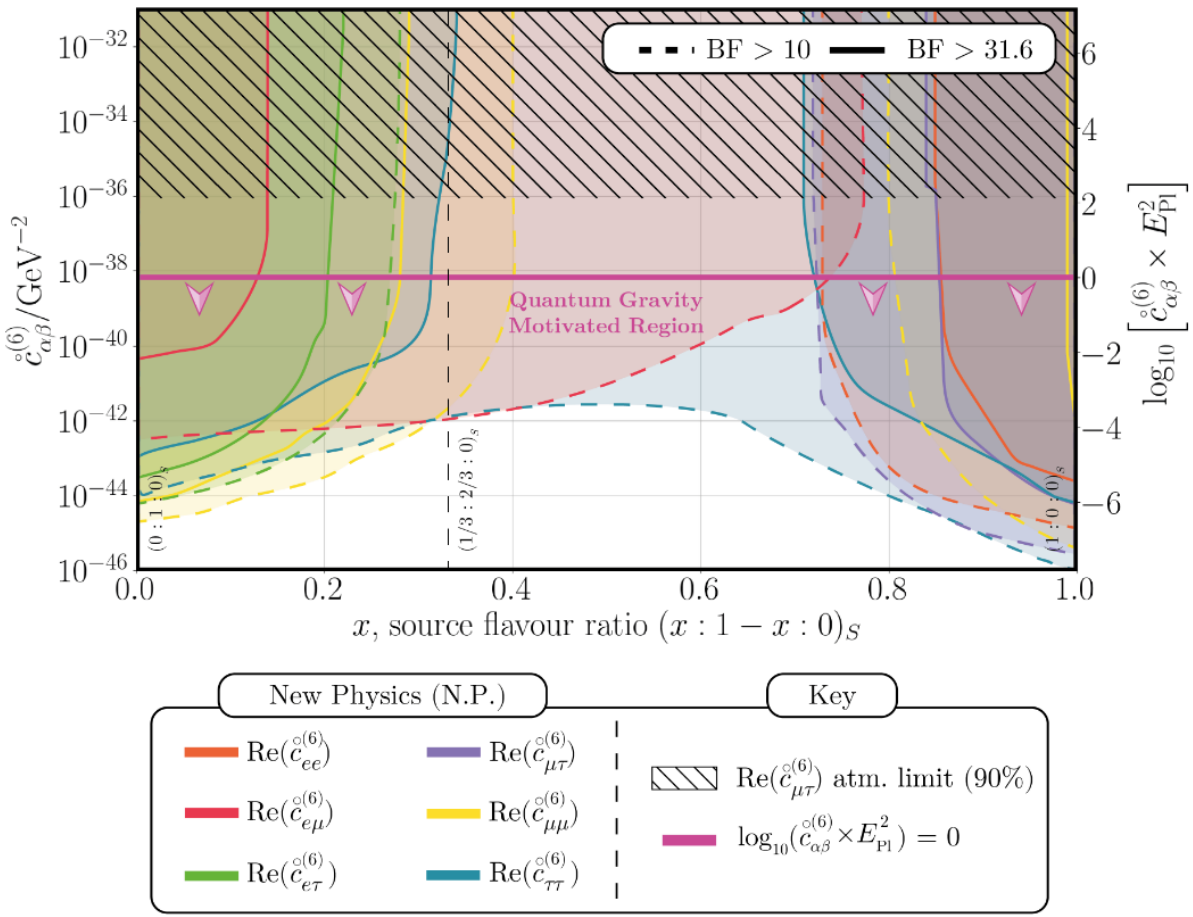
Modelled as effective operators in vacuum Hamiltonian

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots .$$

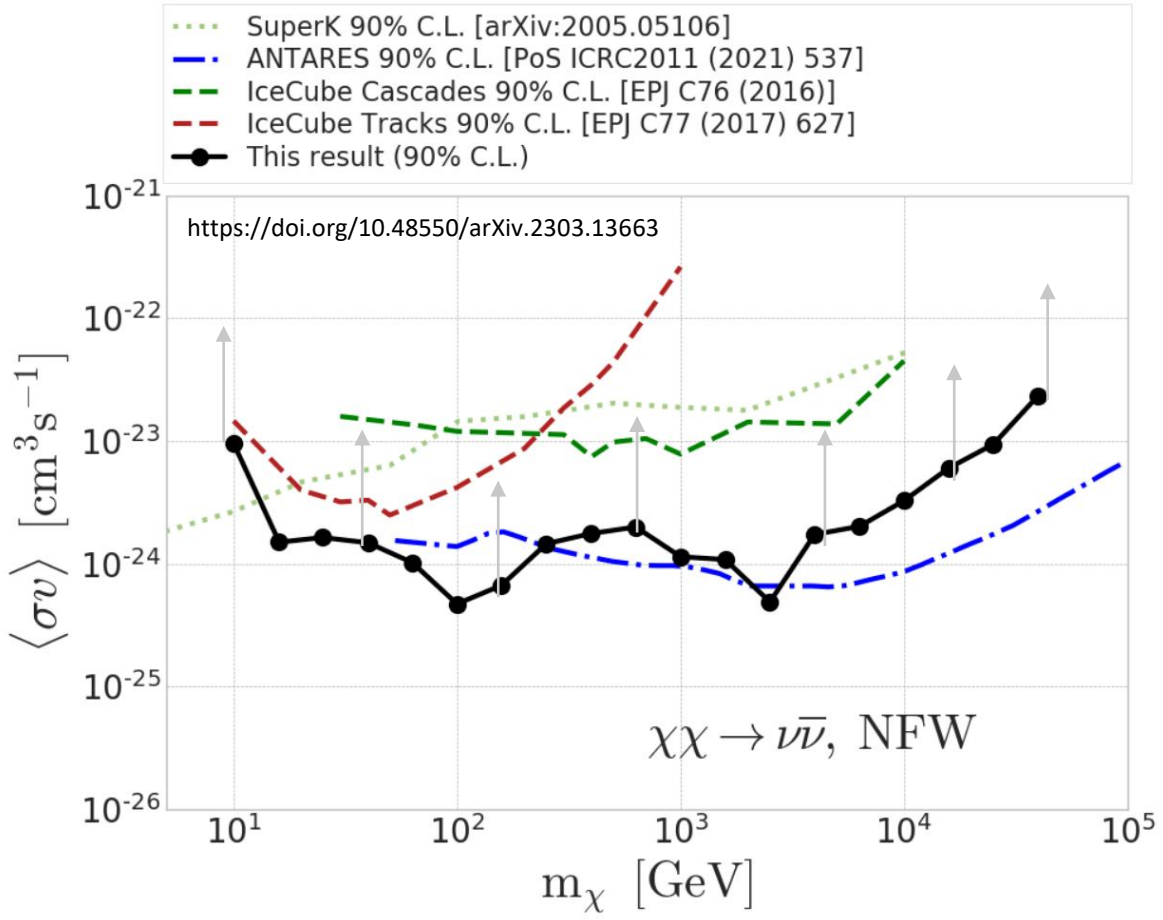
Quantum Gravity

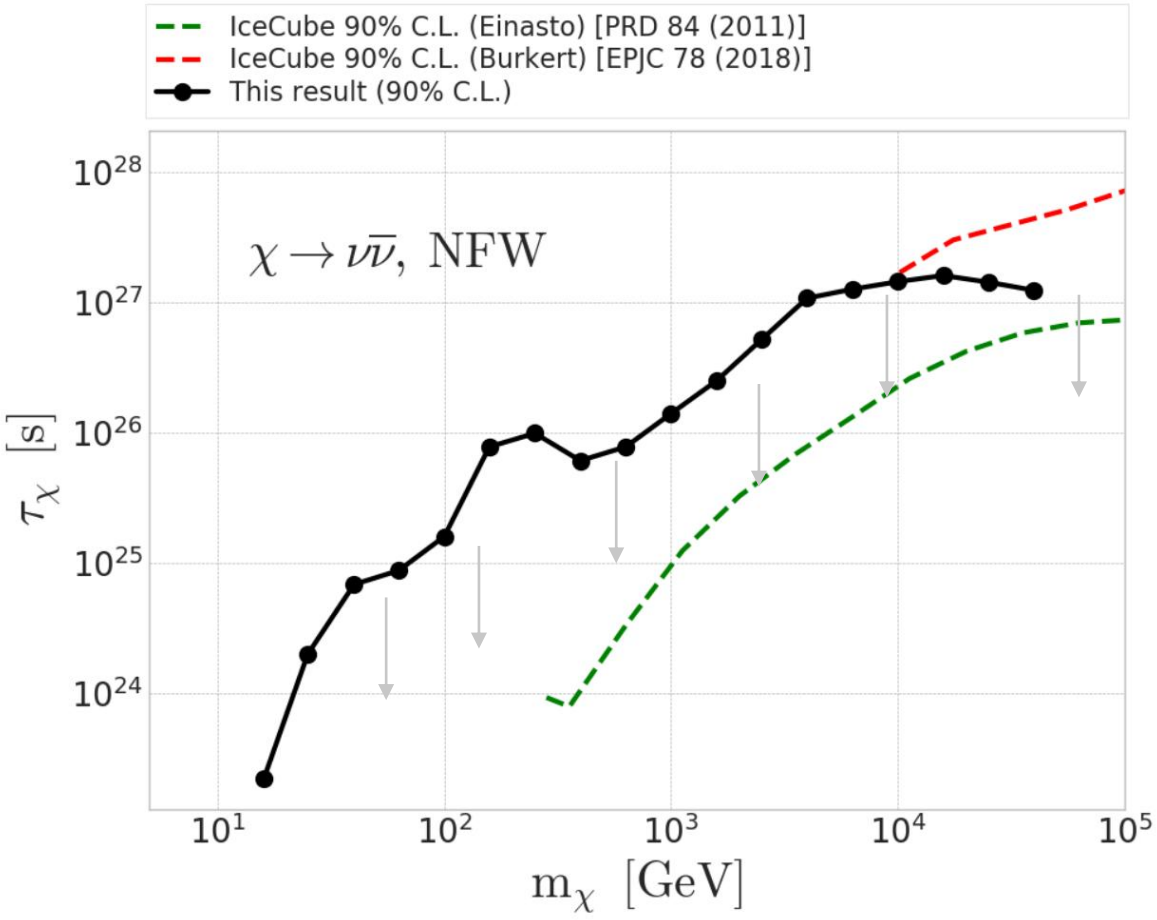
https://doi.org/10.1038/s41567-022-01762-1





Dark Matter Line Search





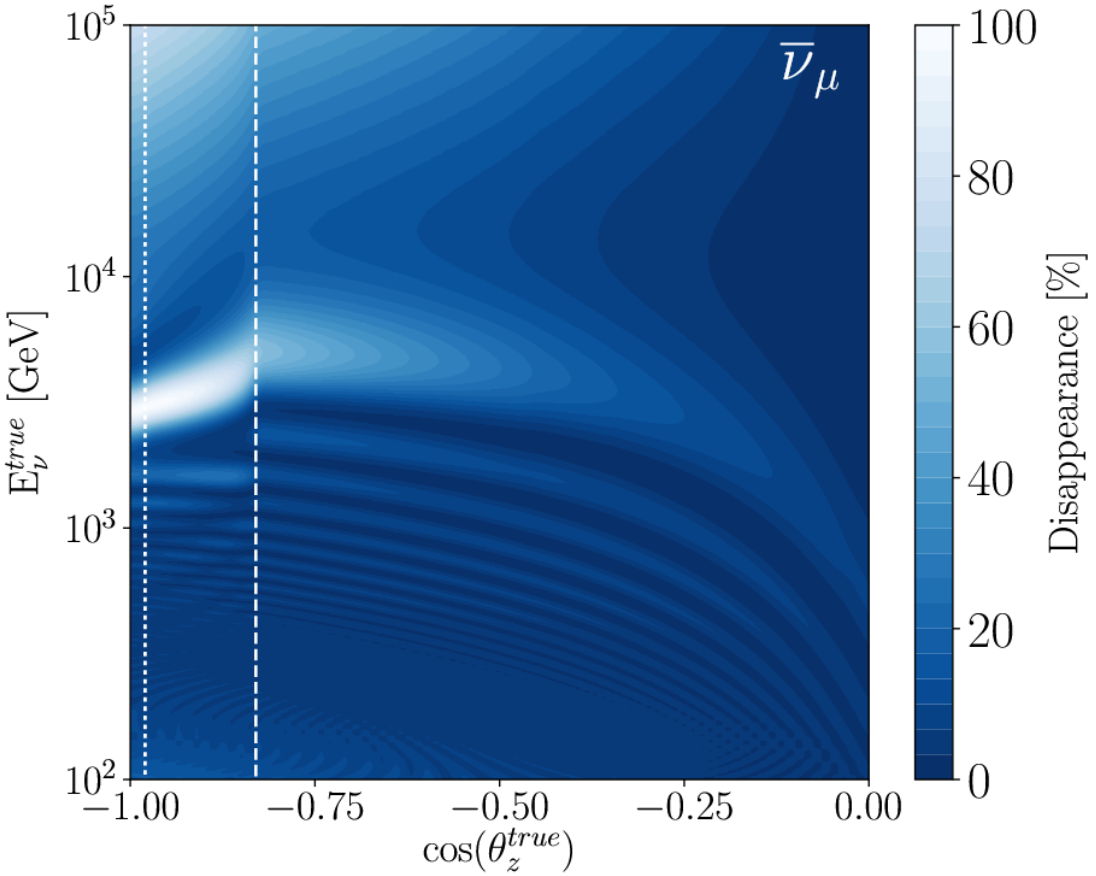
Summary & Conclusions

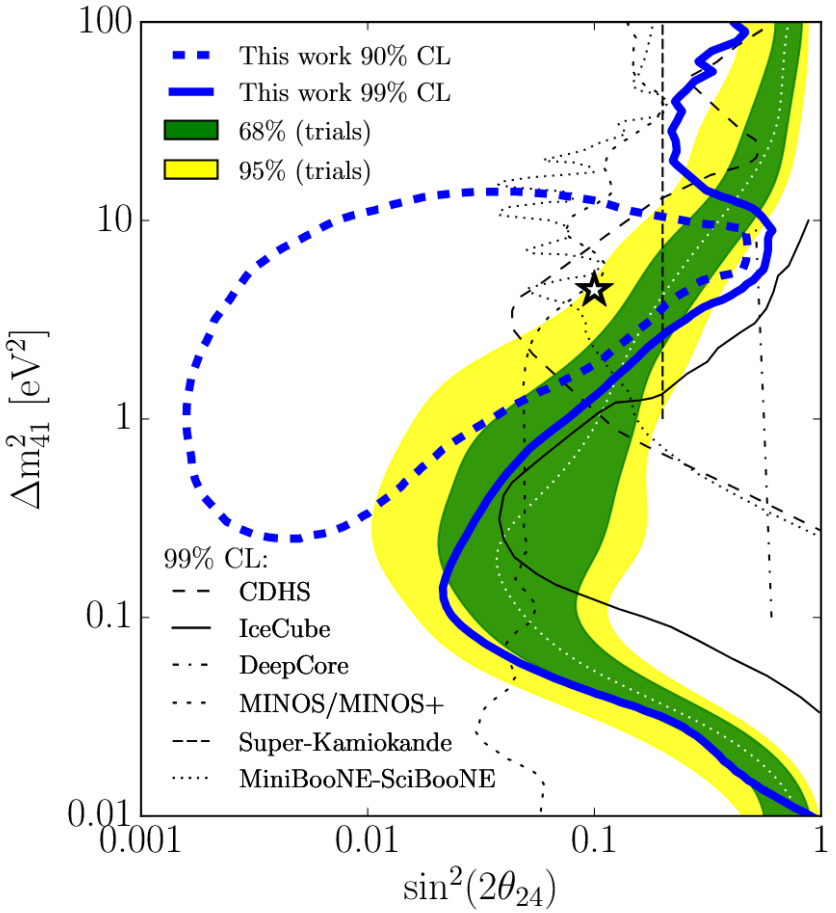
- After the discovery of the flaring blazar TXS 056+056 in 2017, IceCube has identified two additional sources of high-energy neutrinos
- Neutrino emission from the Galactic Plane has been found using the cascade channel (also seeing strong hints in track channel)
- NGC 1068 has been identified as a source of energetic neutrinos (4.2σ)
  => Searches for neutrino emission from other Seyfert Galaxies so far inconclusive
- IceCube is a versatile instrument – many analyses covering topics from particle physics over neutrino physics, to physics beyond the standard model.

Backup

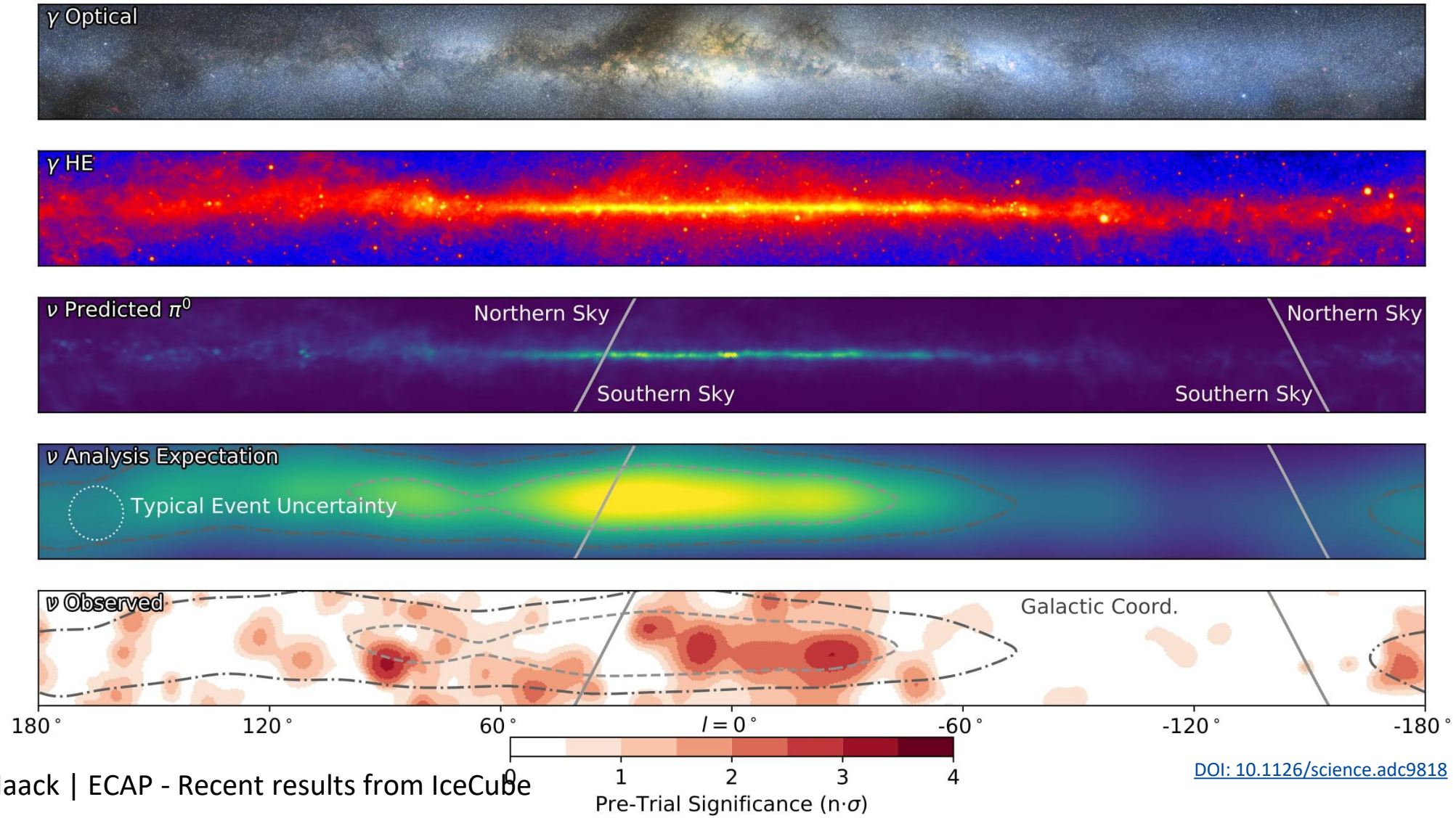
Sterile Neutrinos (3+1)

https://doi.org/10.1103/PhysRevD.102.052009
https://doi.org/10.1103/PhysRevLett.125.141801





Neutrinos from the Galactic Plane



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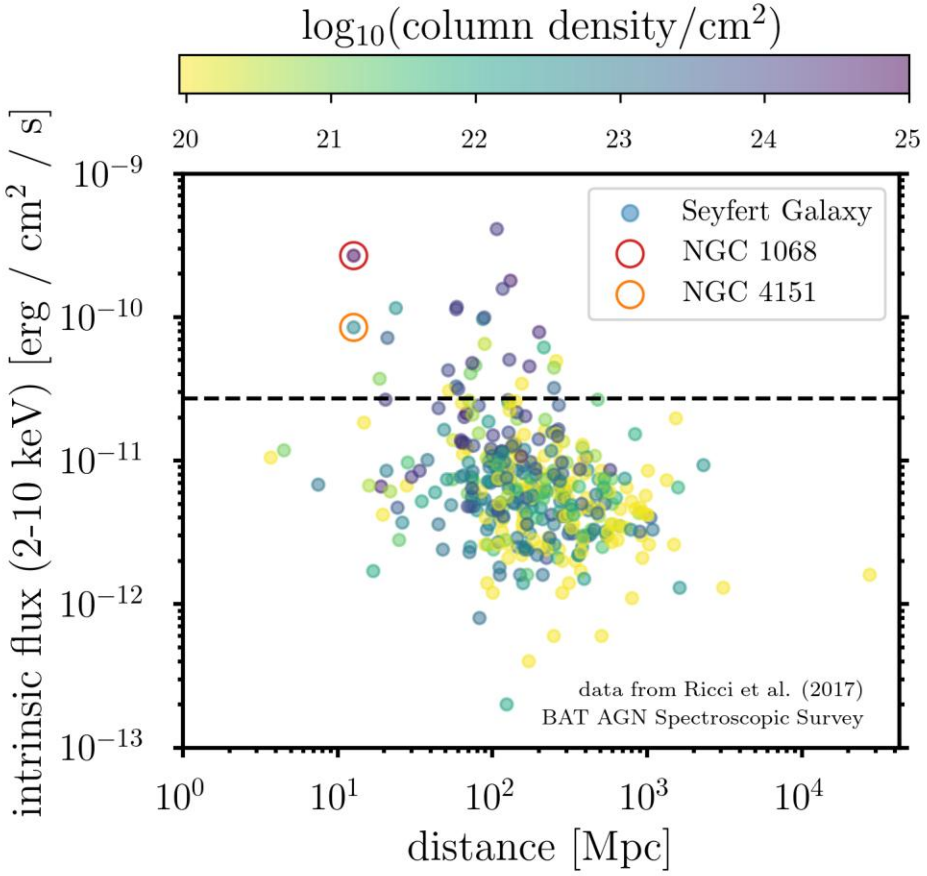
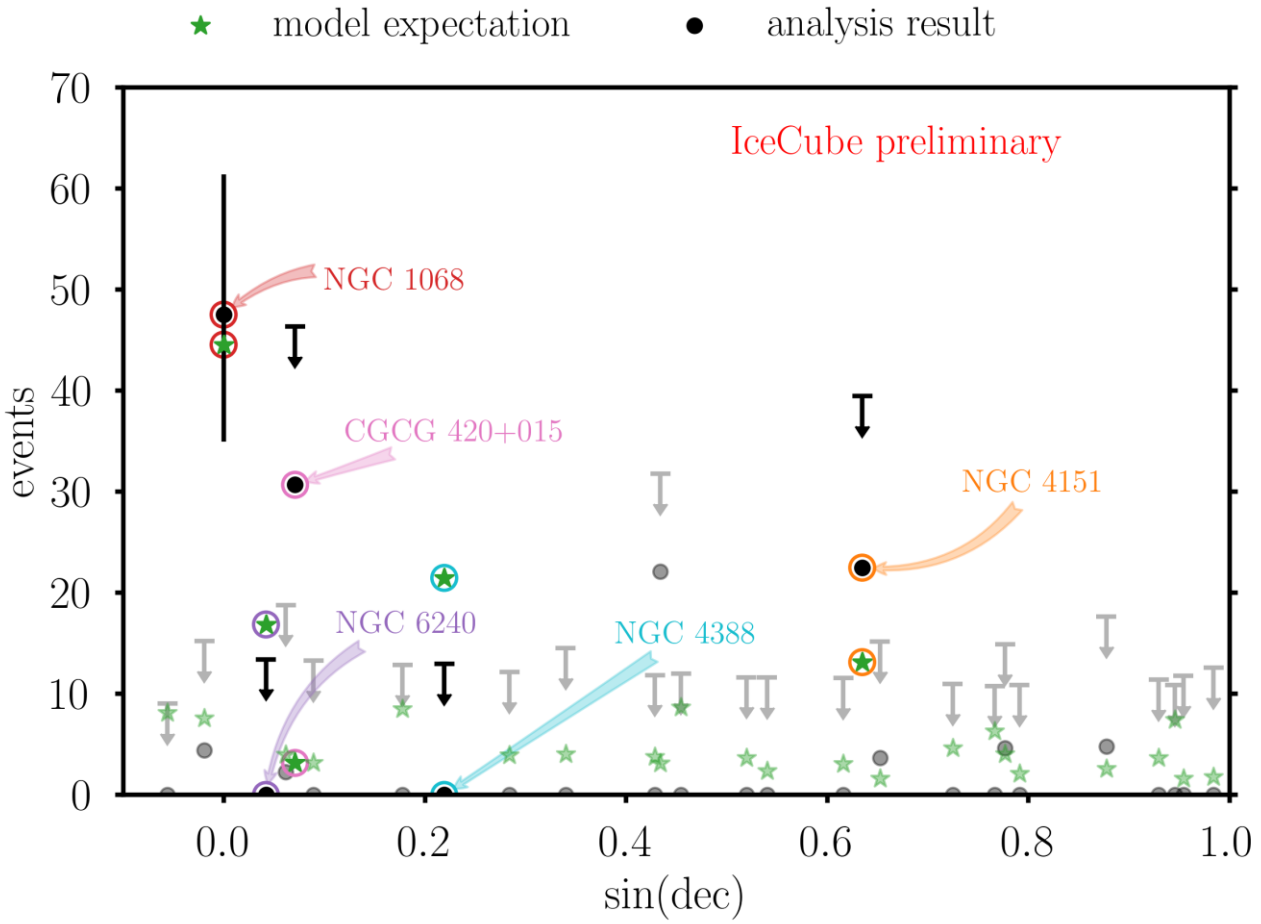
Seyfert Galaxies

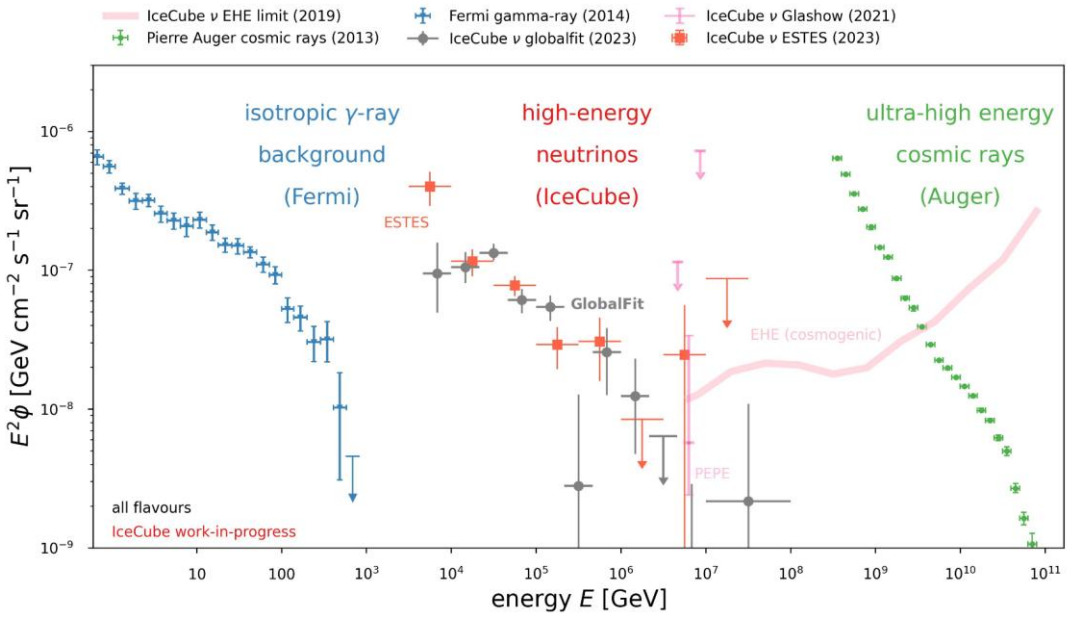


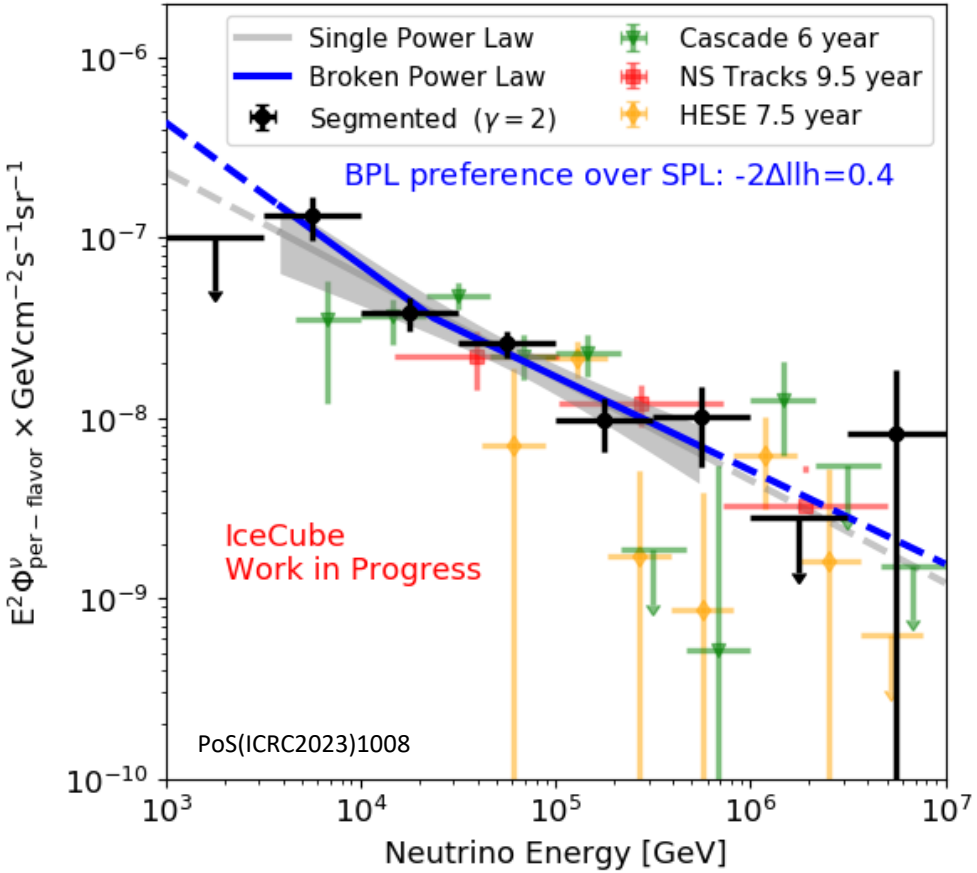


No significant excess found

Cosmic Neutrino Spectrum

New measurements using starting tracks (ESTES)

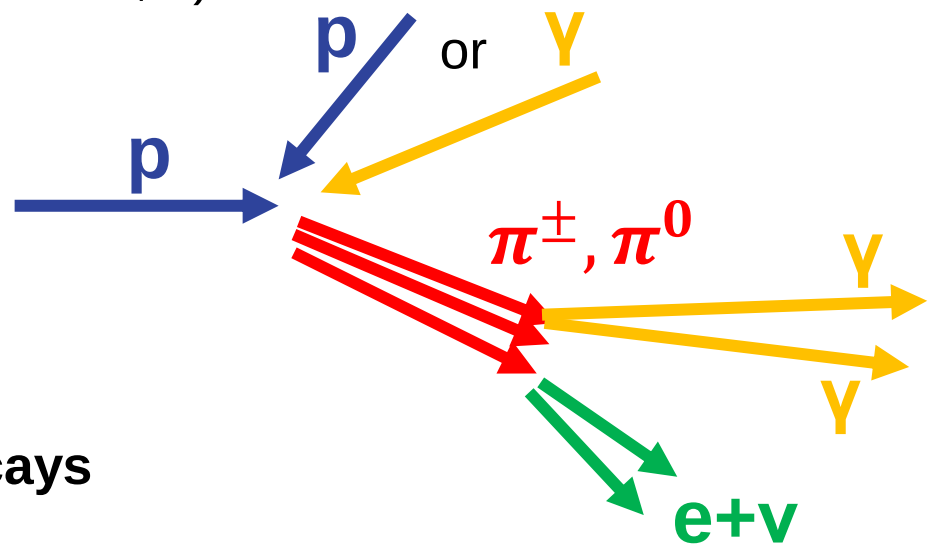




The Cosmic Ray Connection

Accelerator (AGN, SNR, GRB, ..)

DESY



Idealized scenarios

$$p + p \rightarrow X + \begin{cases} \pi^+ & 1/3 \\ \pi^- & 1/3 \\ \pi^0 & 1/3 \end{cases}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 & 1/3 \\ n + \pi^+ & 2/3 \end{cases}$$

Pion Decays

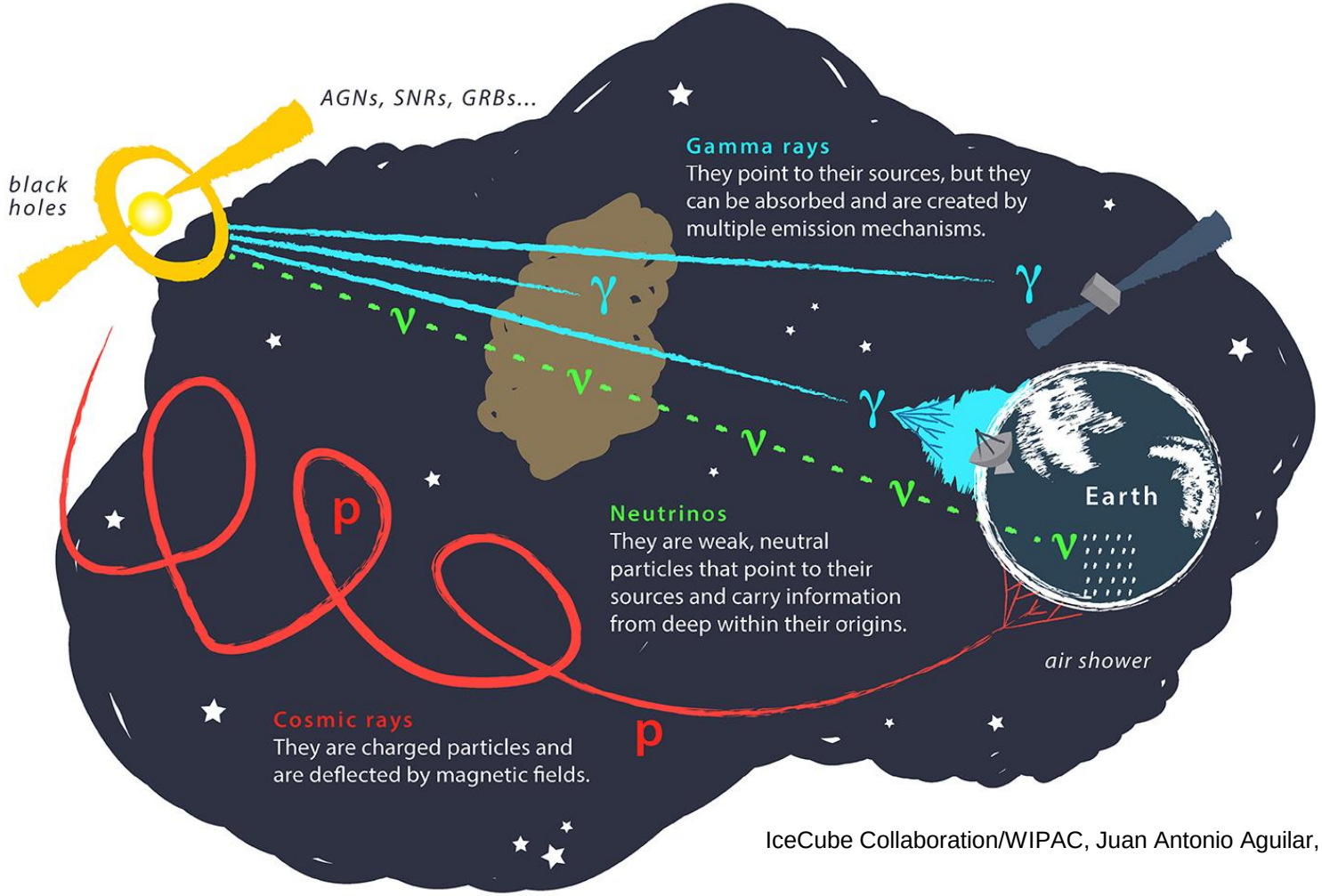
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

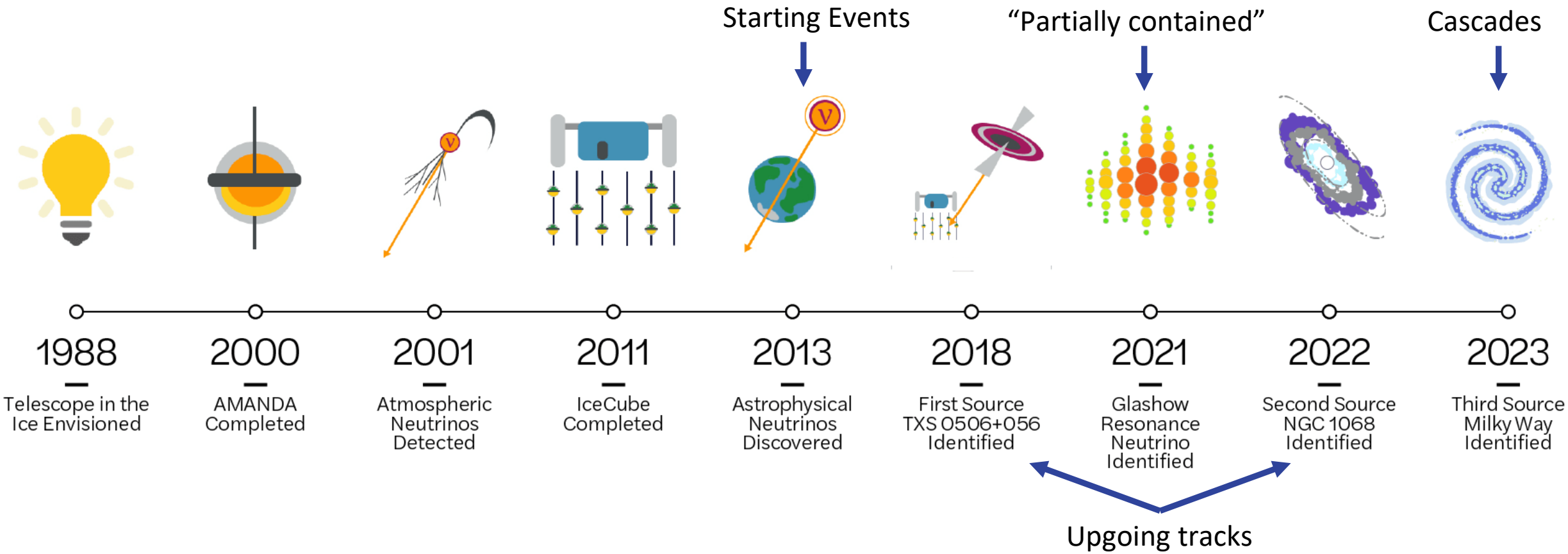
Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays

Neutrinos are ideal messengers

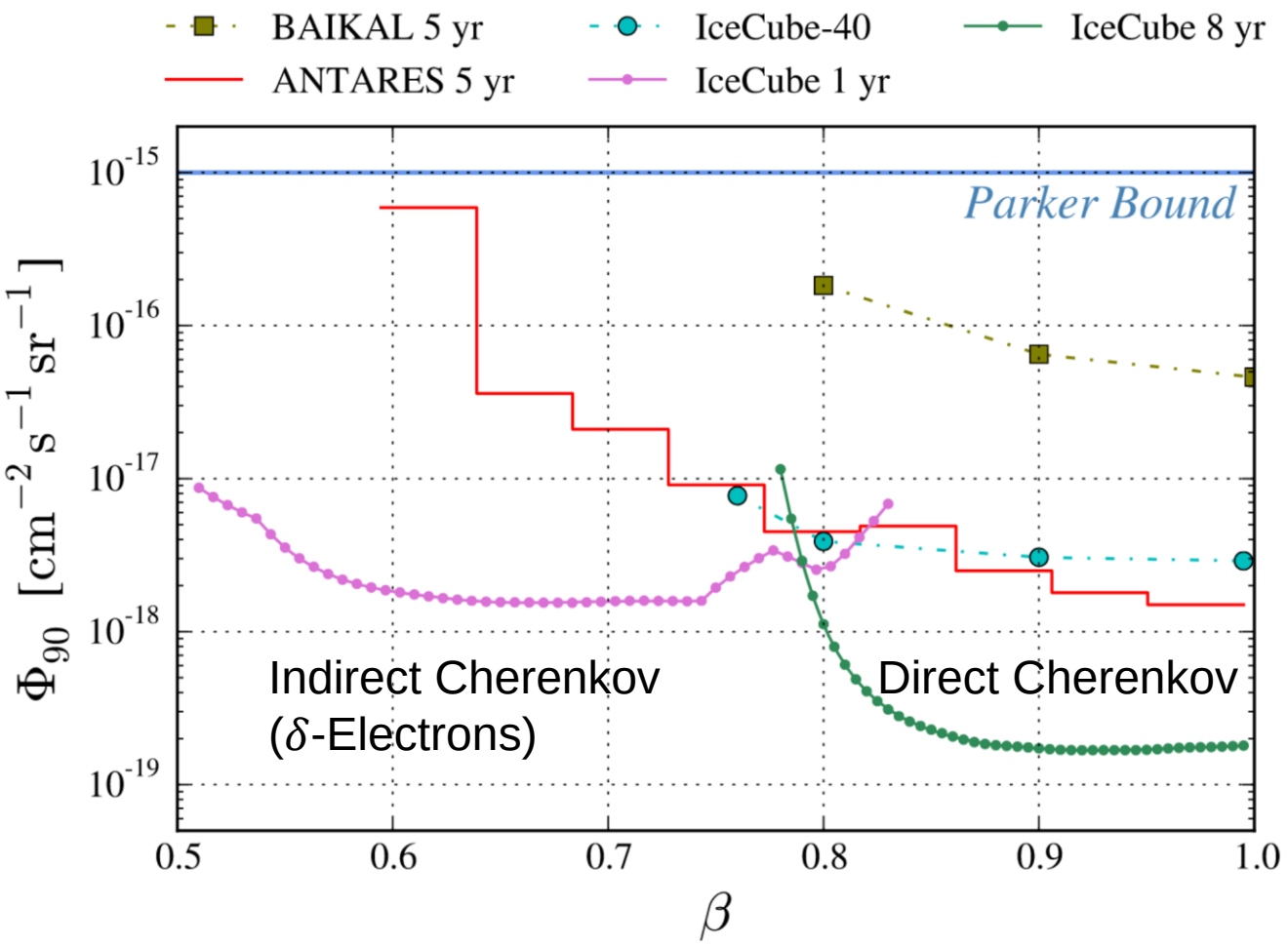


IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang

A History of Neutrino Astronomy in Antarctica

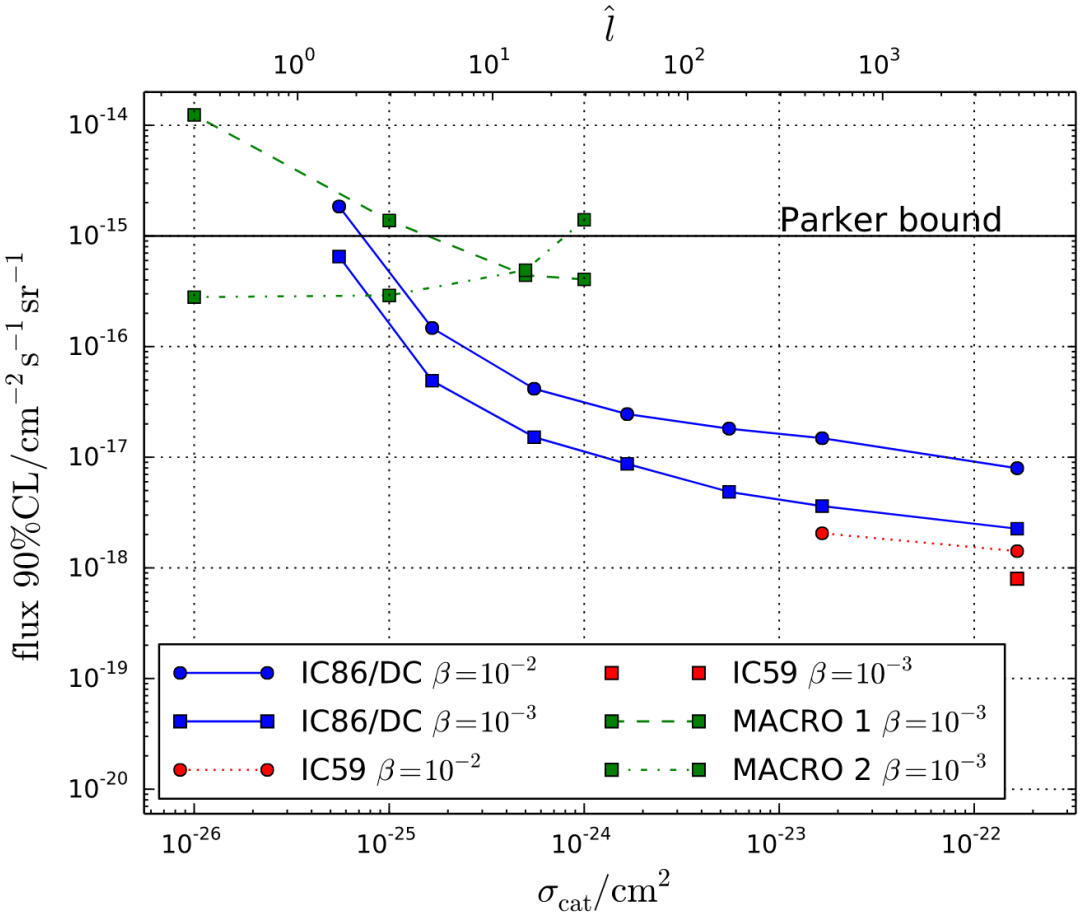


Relativistic Magnetic Monopoles



- ‘t Hooft-Polyakov Monopole
- $\left(\frac{g_D n}{e}\right)^2 \approx 8200$ more photons than electrically charged particle of same velocity

Subrelativistic Mag. Monopoles



Monopole induces proton decay (Rubakov-Callan Effect)